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Mod-2 Wind Turbine System Cluster Research Test Program

Volume I—Initial Plan

Larry H. Gordon
National Aeronautics and Space Administration
Lewis Research Center

March 1982

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind Energy Technology Division

NOTICE

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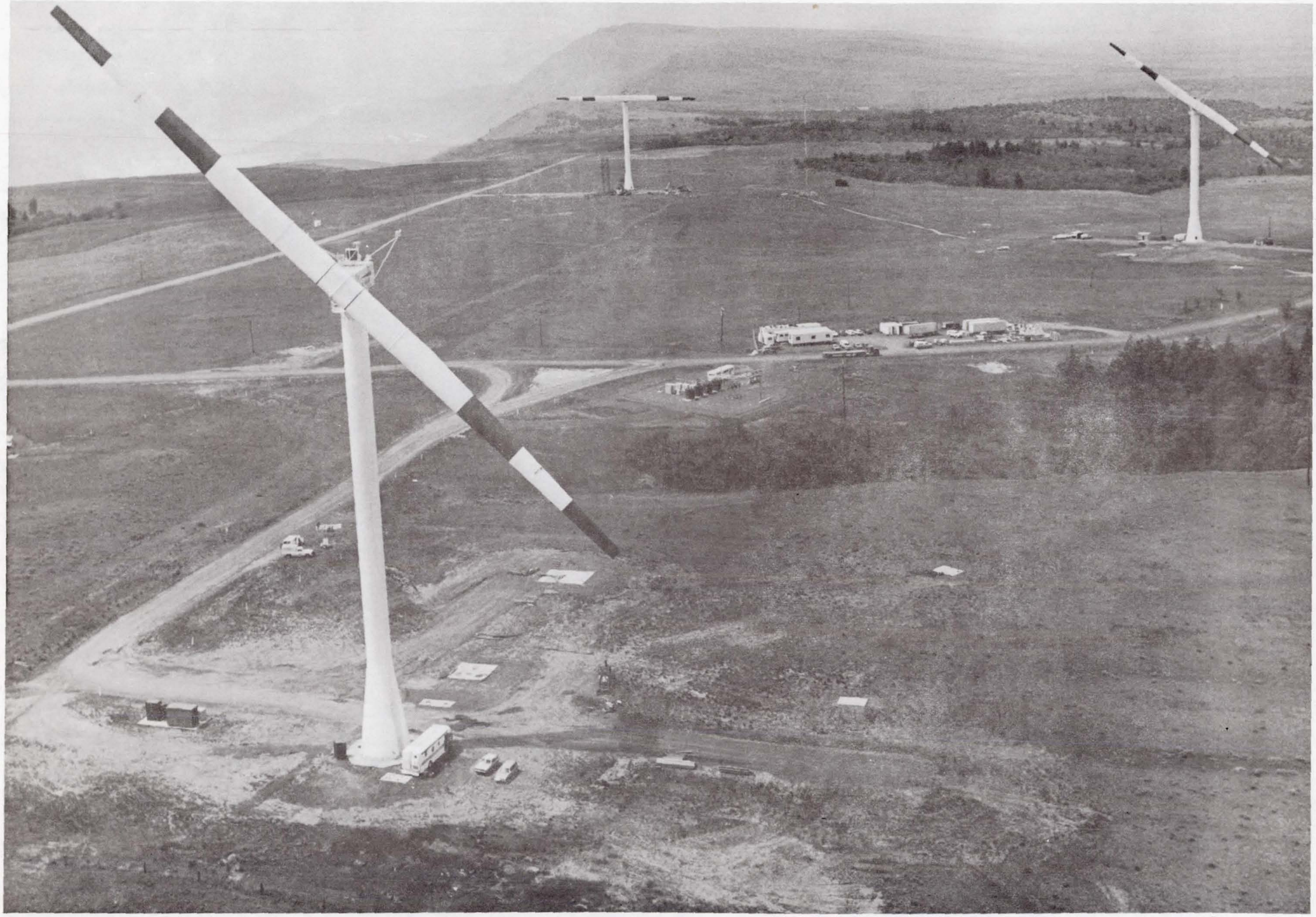

Mod-2 Wind Turbine Cluster Test Site (Goodnoe Hills, Washington).

FOREWORD

At the request of the Department of Energy (DOE), Division of Wind Energy Technology, this draft program plan was prepared to describe the specific research tests for, as well as the overall operation of, the Mod-2 wind turbine cluster test site located near Goldendale, Washington. Inputs to the plan were provided by a research test project review team consisting of representatives of Bonneville Power Administration (D. Seely, R. Holeman, N. Butler, and E. Warchol), Boeing Engineering and Construction Company (R. Axell, H. Woody, M. Rees, and D. Fries), Battelle Pacific Northwest Laboratory (D. Renne, D. Hadley, and W. Sandusky), and the Solar Energy Research Institute (N. Kelly). Lead management for drafting the program plan was assigned to the NASA Lewis Research Center's Wind Energy Project Office.

It is the intent of the DOE and NASA to provide this draft planning document to the private sector for information and critique. The Government is neither committed nor obligated to enact any part of the subject plan.

CONTENTS

ABBREVIATIONS

BEC	Boeing Engineering and Construction Company
BPA	Bonneville Power Administration
CRT	Cathode Ray Tube (Control Console)
CY	Calendar Year
DATS	Dial Automatic Telephone Switching
DOE	Department of Energy
EIS	Engineering Instrumentation System
KV	Kilovolts
kW	Kilowatt
LeRC	Lewis Research Center (NASA)
LTPO	Lead Test Project Organization
Met	Meteorological
MW	Megawatt
NASA	National Aeronautics and Space Administration
o.d.	Outside Diameter
PNL	Pacific Northwest Laboratory (Battelle)
PUD	Public Utility District
rpm	revolutions per minute
SERI	Solar Energy Research Institute
STD	Standard Temperature Day
TBD	To Be Determined
TPRB	Test Project Review Board
TVI	Television Interference
UHF	Ultra High Frequency
WEPO	Wind Energy Project Office (LeRC)
WIND-REAP	Wind Regional Energy Assessment Program
WTG	Wind Turbine Generator
WTS	Wind Turbine System

1.0 INTRODUCTION

1.1 Background

Within the Federal Wind Energy Program, the U. S. Department of Energy (DOE) Office of Solar Electric Technologies has overall responsibility for conceiving and directing research and development of wind energy systems. The DOE in turn has delegated project management responsibility to the National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC), in Cleveland, Ohio, for the design, fabrication, and field testing of large (100 kW and larger) horizontal-axis wind turbine systems (WTS) for utility applications. The utlimate objective of the Federal Wind Energy Program and the projects by which it is implemented is the development of the technology base necessary for cost effective wind-powered generation of electricity by private industry.

The MOD-2 wind turbine project is the first in the Federal Wind Energy Program to be dedicated to the design, installation and research testing of an experimental wind turbine system at a rated power of 2.5 MW. The installatiaon of three such machines clustered at a single site at Goldendale, Washington is planned to be available for this test program which will research, test and evaluate the interactive and machine/grid effects of multiple, identical, machines integrated into a utility network.

The DOE selected the Bonneville Power Administration (BPA) as the participating utility for the Mod-2 wind turbine project. This utility is a large regional power marketing and transmission organization in the Pacific Northwest and has the capability of providing valuable support in attainment of the DOE/NASA project goals in the federal Wind Energy Program as well as part of the BPA Wind Regional Energy Assessment Program (WIND-REAP).

The Boeing Engineering and Construction Company (BEC) is under contract to NASA LeRC as the Test Facility Operations Contractor, to provide support for research test operation and maintenance of this cluster.

At the request of the DOE Division of Wind Energy Technology, this research test project plan was prepared by NASA LeRC Wind Energy Project Office with support from the MOD-2 Contractor, BEC. Inputs to the plan were provided by Lead Test Project Organization participants consisting of representatives of Bonneville Power Administration, Boeing Engineering and Construction Company, Solar Energy Research Institute, Battelle Pacific Northwest Laboratories, and the LeRC. Lead test center planning, management, and coordination for this Mod-2 test program, as well as the drafting of this plan, were assigned to LeRC.

A Mod-2 Test Project Review Board (TPRB), co-chaired by NASA LeRC and BPA and with membership of all lead test project organization provides guidance and approval of all planned testing.

1.2 Purpose

This test project plan provides information on the research testing planned by the TPRB. It describes the facility available for this test program as well as plans for specific tests, including objectives, test methods and data to be collected. It is the intent of the DOE to provide this draft test project planning document to the private sector for information. The government is neither committed nor obligated to enact any part of this plan.

1.3 Scope

This plan is divided into two volumes. Volume I, initial plan distributed to the private sector, includes information on the program objectives, a Mod-2 system description, a planning schedule, organizational roles and responsibilities, the test facility, the test methods and a summary of planned testing.

Volume II, a continuously updated test operations document, provides detailed test plans of specific tests prepared by the lead test organization and approved by the TPRB. The test plans describe the work to be accomplished in terms of several tasks. Within the description of each task, the test plan states test objectives, conditions, facility requirements, operational impact, test matrix, data acquisition/reduction, documentation, resources and schedule. Since Volume II is primarily a working document, distribution will be limited.

2.0 TEST PROGRAM OBJECTIVES

2.1 General

In accordance with current priorities of the DOE Office of Solar Electric Technologies, primary emphasis will be placed on the field research test operation of the wind turbine cluster. Specifically, research areas to be addressed pertain to: 1) Aerodynamics; 2) Structural dynamics and aeroelasticity; 3) Materials characteristics and fatigue testing; and 4) Multiple systems interactions. In addition, the cluster can also be utilized as an experimental test bed for supporting related wind energy system research.

The general objective of the MOD-2 WTS Cluster Research Test Program is to evaluate interactive and machine/grid effects of large, clustered, multi-megawatt wind turbines integrated into a utility network. The program is also structured to provide data valuable to the continued research of wind energy systems.

2.2 Specific

Specific objectives of the test program will be developed as part of the detailed planning performed by the Lead Test Project Organization and the TPRB.

Preliminary planning indicates the following research objectives will include:

a. Evaluation of single and multiple machine performance and operating characteristics.

b. Evaluation of single and multiple machine impacts on the local power grid.

c. Determination of wake interaction effects.

d. Evaluation of environmental aspects (noise, TV interference [TVI] etc.)

e. Cluster/array analysis (3 machines/20 plus machines).

f. Array maintenance evaluation.

g. Advanced concepts verification.

3.0 SYSTEM DESCRIPTION

3.1 General

The MOD-2 wind turbine system is being developed for the DOE and the NASA/LeRC by BEC under Contract DEN 3-2. Installation and checkout of three clustered MOD-2 units has been completed at the project site known as Goodnoe Hills, near Goldendale, Washington (see map Fig. 3.1-1). The units provide power into BPA's high voltage transmission network through the Klickitat County PUD electric power grid. A substation at the site, known as Goodnoe Hills Substation, provides the power interface between the three units and the utility transmission lines. (See Fig. 3.1-2)

The general configuration and characteristics of a MOD-2 wind turbine unit are shown in Fig. 3.1-3 and a plot of power output versus wind speed is shown in Fig. 3.1-4. A detailed technical description of the unit may be found in references 1 to 3.

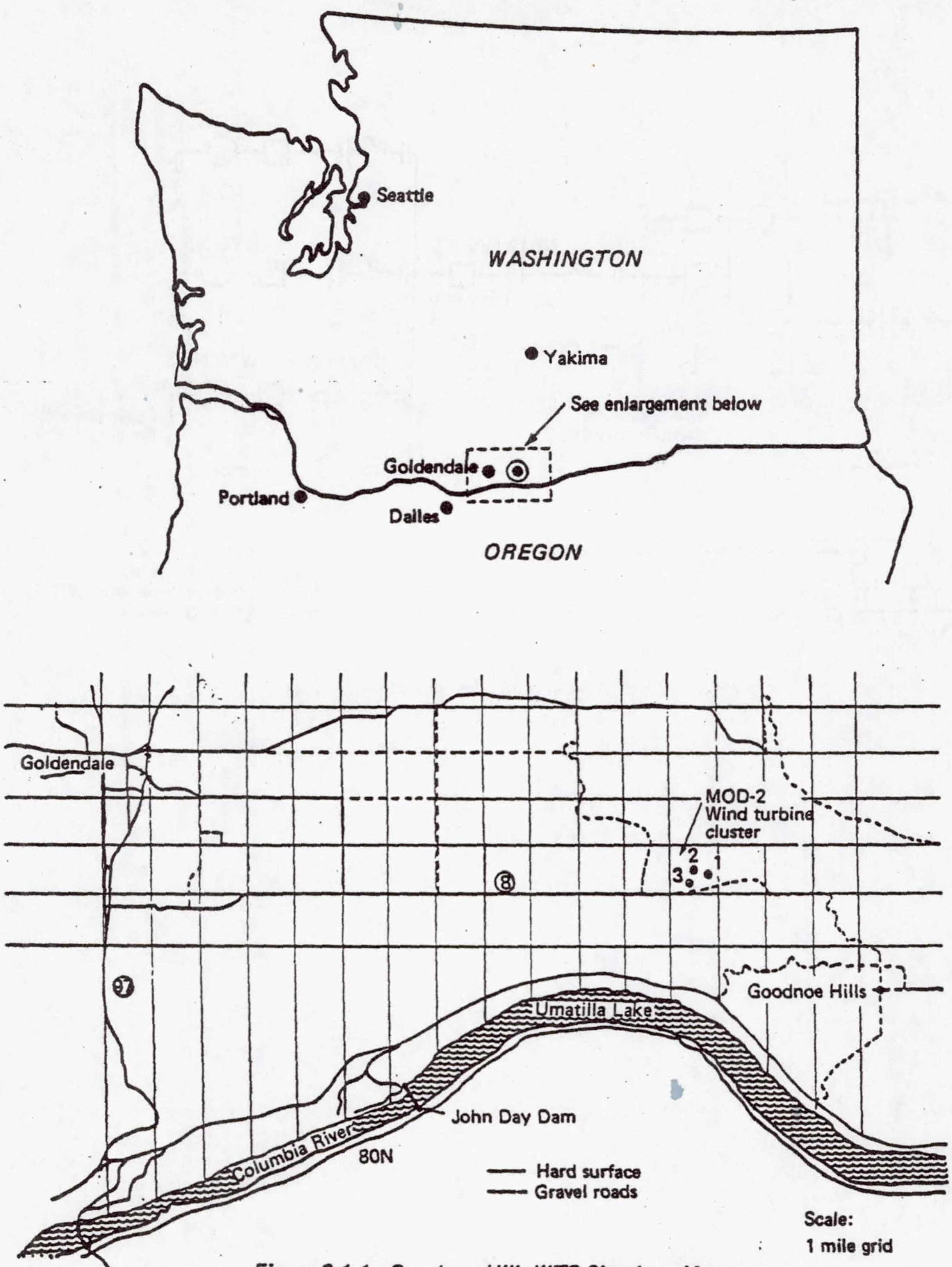

Figure 3.1-1. Goodnoe Hills WTS Site Area Map

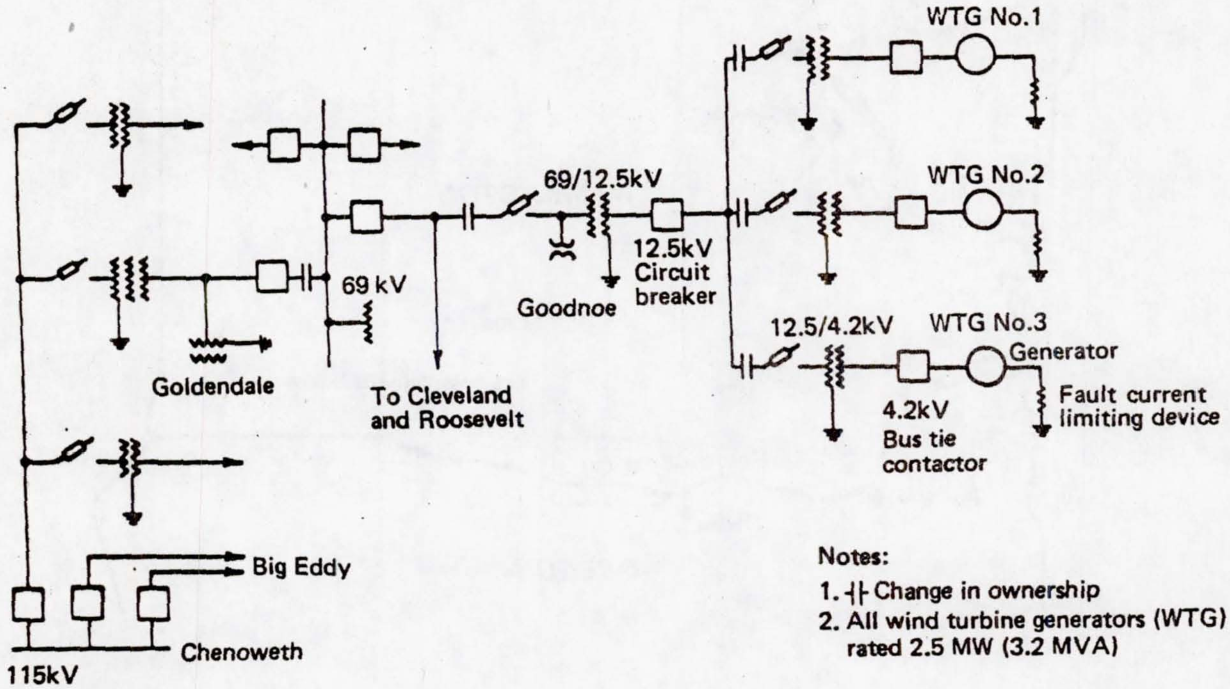

Figure 3.1-2. Goodnoe Hills Transmission System

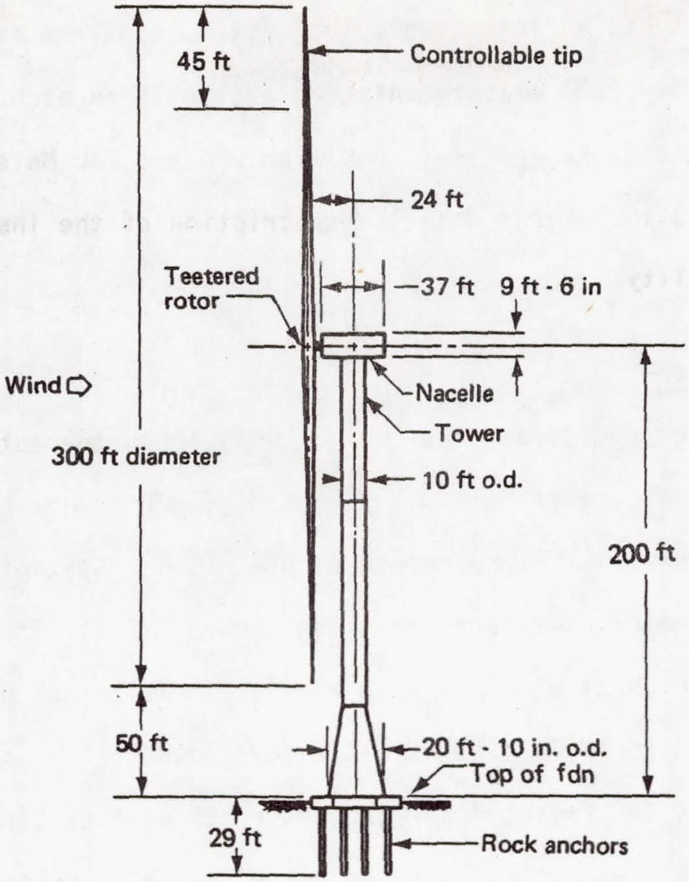

Figure 3.1-3. MOD-2 General Configuration and Features

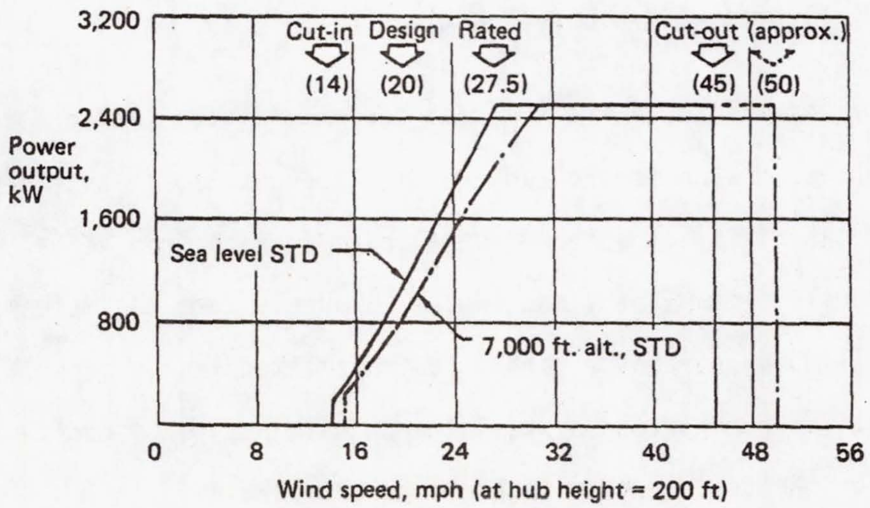

Figure 3.1-4. MOD-2 Power Output versus Wind Speed

Each wind turbine unit has an instrumentation system installed for gathering engineering data. Eighty (80) measurements are available on each unit and in addition, meteorological data are available from BPA and PNL Meteorological Towers. Paragraph 6.3 includes a detailed description of the installed data system and its capability.

3.2 Normal Operation

Under normal operating conditions, the cluster will be in the automatic mode, initiated either at the site (from a CRT keyboard at each tower base) or from the remote control facility (CRT keyboards at BPA Dittmer Control Center, Vancouver, WA.) via a microwave data link (see Figure 3.2-1). In this condition, the wind turbine units will start up when the operational wind sensors detect sufficient wind speed is available for power generation (nominally greater than 14 mph at 200 feet)*. After the rotor has accelerated up to 17.5 rpm, the generator will automatically synchronize to the power system grid and supply power to the utility network. Automatic monitoring of the system performance continues throughout the operation and status is available locally at the site (CRT at the tower base) and at the remote control facility (CRT at BPA Dittmer Control Center, Vancouver, WA.).

Engineering data and wind data will be recorded at the data center located near WTS #2 whenever the units are running. The present configuration provides for a recording capability of up to 40 data channels each from WTS #1 and WTS #3, 64 data channels from WTS #2, and 18 data channels from the meteorological towers. Since all 80 measurements cannot be transmitted from each unit to the data center, the instrumentation system at each unit has to be configured prior to test for the desired data channels to be recorded.

*Unless otherwise noted, all measurements of wind speed are in mph measured at hub height (200 ft. above ground level).

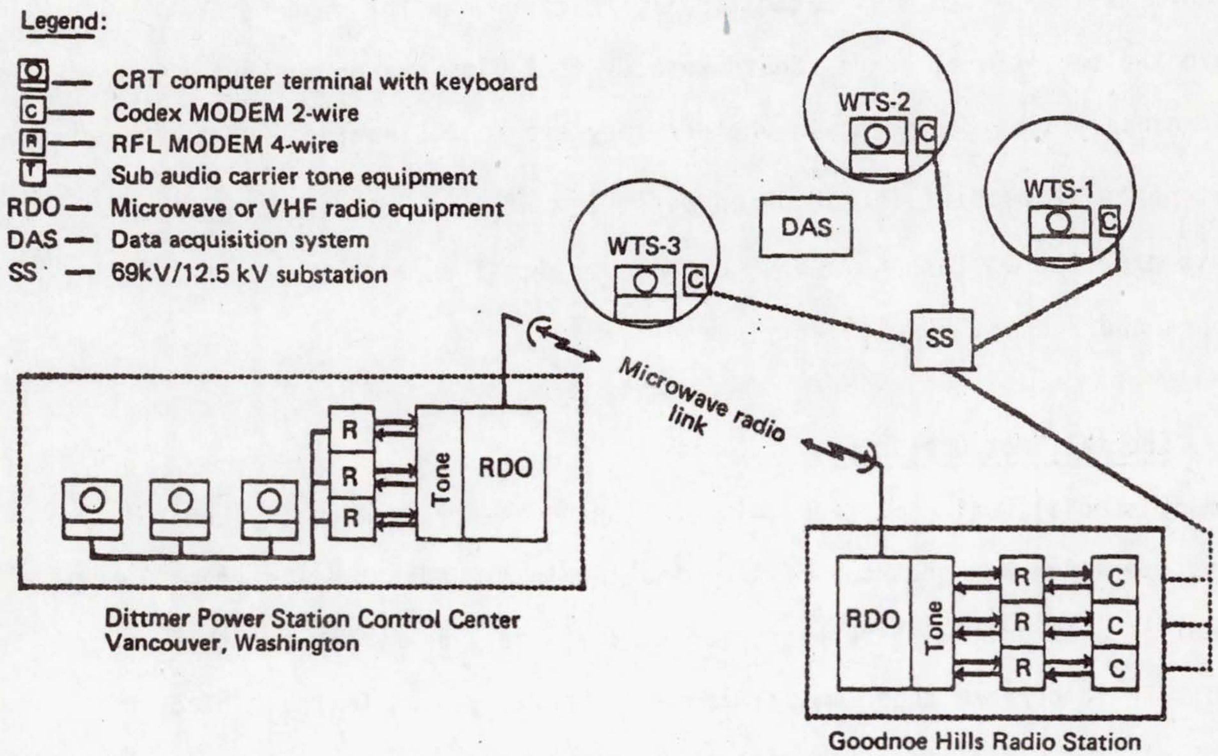

Figure 3.2-1. Goodnoe Hills WTS Remote Control, Functional Block Diagram

A normal shutdown will occur if the wind speed falls outside the operational range of the system (14 to 45 mph); however, no action is necessary to restart the unit as the system will automatically restart when the wind returns to within the operational range. Shutdowns due to faults may or may not require a maintenance action depending on whether they are self-clearing or not. Normal maintenance (2 people) is scheduled every 2 months, 6 months and 12 months and is expected to take a machine out of service for periods of 6 hours, 8 hours and 3 days, respectively.

3.3 Special Test Operation

For many special test conditions, it will be necessary to manually control the start, operation and shutdown of the wind turbines. Under these circumstances, control of each unit will be performed at the site. The system has the capability to perform under manual command for (a) yawing (without blade rotation), (b) blade tip pitch control (without blade rotation), and (c) rotation up to 8 rpm (with winds from 14 to 27 mph). In addition, normal shutdowns (slow) and emergency shutdowns (fast) can be commanded at any time from the CRT room at the base of the tower. It is recognized that for special operations of the wind turbines, the test conditions will have to be coordinated with the Test Facility Operator (BEC) and BPA and a workable test plan and procedure developed.

4.0 SCHEDULE

As previously agreed by NASA/DOE, this research test plan shall be effective for a period of 30 months, subject to a 24-month extension by mutual agreement. As illustrated in Fig. 4.0-1, the overall project schedule is shown from CY 1981 to the end of CY 1984.

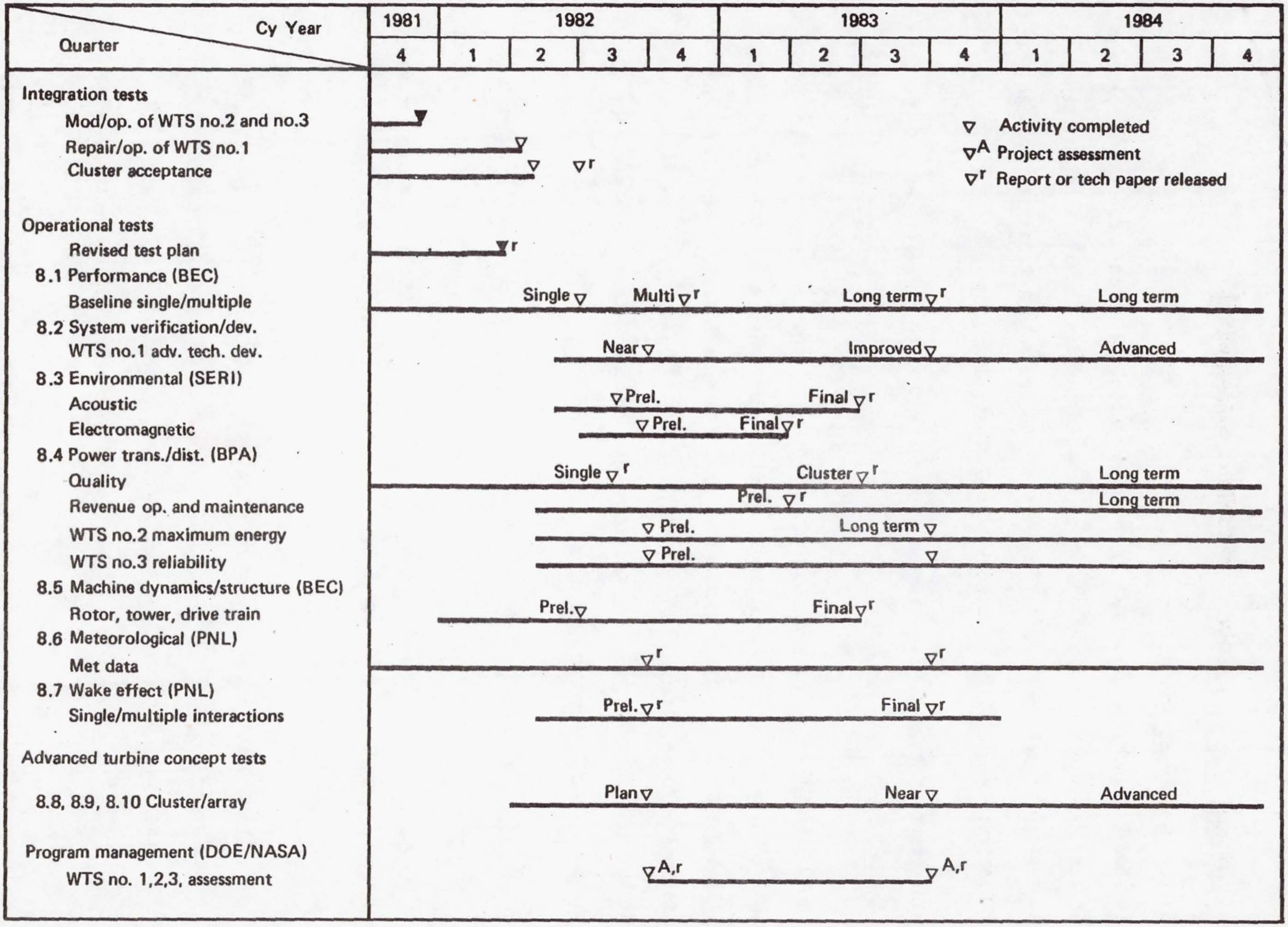

Figure 4.0-1. MOD-2 Cluster Research Test Program - Master Schedule

5.0 MANAGEMENT PLAN

5.1 Management Approach

The MOD-2 Cluster Turbine Test Program encompasses a broad and diverse spectrum of activities and organizations which require coordinated planning, continuous evaluation of progress and full communication and interaction with DOE and with the appropriate utility, commercial and industrial sectors.

Management of this program will be in accordance with the policies and procedures set forth by DOE/NASA. Fig. 5.1-1 shows the management structure.

The DOE Large Wind Technology Branch has overall program responsibility for this effort. The program management functions at Lewis Research Center (LeRC) will be performed in the Wind Energy Project Office located in the Wind and Stationary Power Systems Division of the Energy Programs Directorate. Mr. L. H. Gordon is the MOD-2 Research Test Program Manager. Key elements of the Lead Test Center management approach are:

1. Program Management - The Lead Test Center will provide overall management including planning, integration and coordination of the involved field test organizations. It will focus on research test activity needed to provide a technical base that will enable the private sector to develop and utilize wind energy systems.

   Program objectives and plans will be formulated and will serve as the basis for an ongoing assessment of progress achieved. The planning process will include continued interaction with the field test organizations and with utility, commercial and industrial participants.

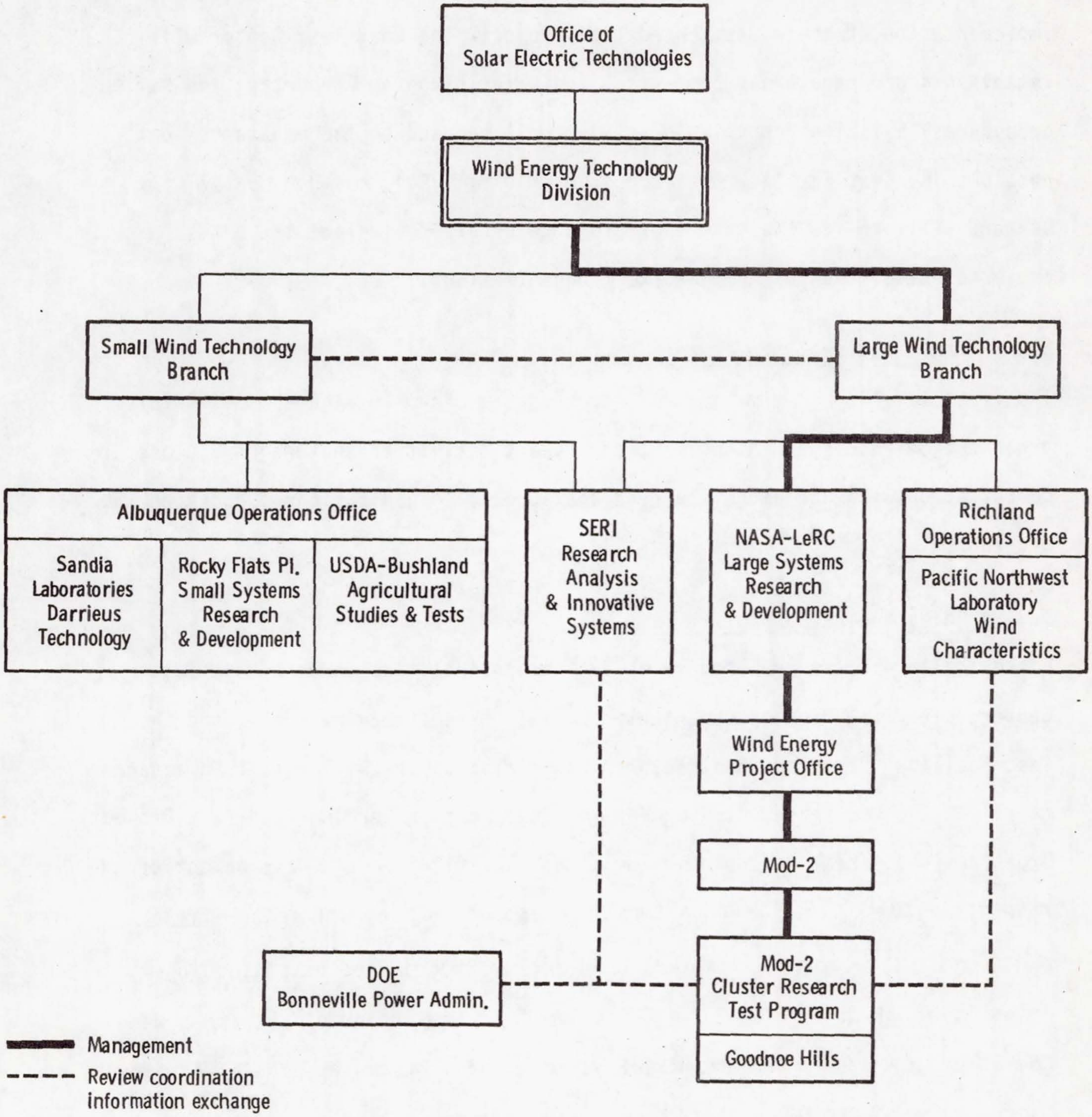

Figure 5.1-1. - Mod-2 Cluster research test program structure.

2. Program Implementation - Lead test organizations will be delegated prime responsibility and appropriate authority for the day-to-day management and implementation of their designated test project. The Lead Test Center will establish broad management processes, including planning, reporting and review procedures. Existing reporting practices will be used to the maximum extent possible. The Test Facility Operations Contractor (BEC), managed by the Lead Center, will provide the test operations necessary to implement the test projects established by the lead test organizations.

5.2 Organizational Structure

The first level program management structure is shown in Figure 5.2-1. This organization addresses the major test project activities that require close coordination with and among the lead test project organizations supporting the program.

5.3 Roles and Responsibilities

Listed below are the proposed roles and responsibilities for the Lead Test Center, Lead Test Project Organizations, Test Project Review Board, and the Test Facility Operations Contractor. Future discussions will result in management Test Project agreements between the Lead Test Center and Lead Test Project Organizations. These will provide detailed clarification and development of the respective roles. DOE Headquarters is responsible for goal setting and management of the overall Federal Wind Energy Program including funding activities involved in the Mod-2 Test Program which are included in the PNL Wind Characteristics Program, the SERI Environmental Programs and the NASA Large Wind Turbine Research and Technology Development Program.

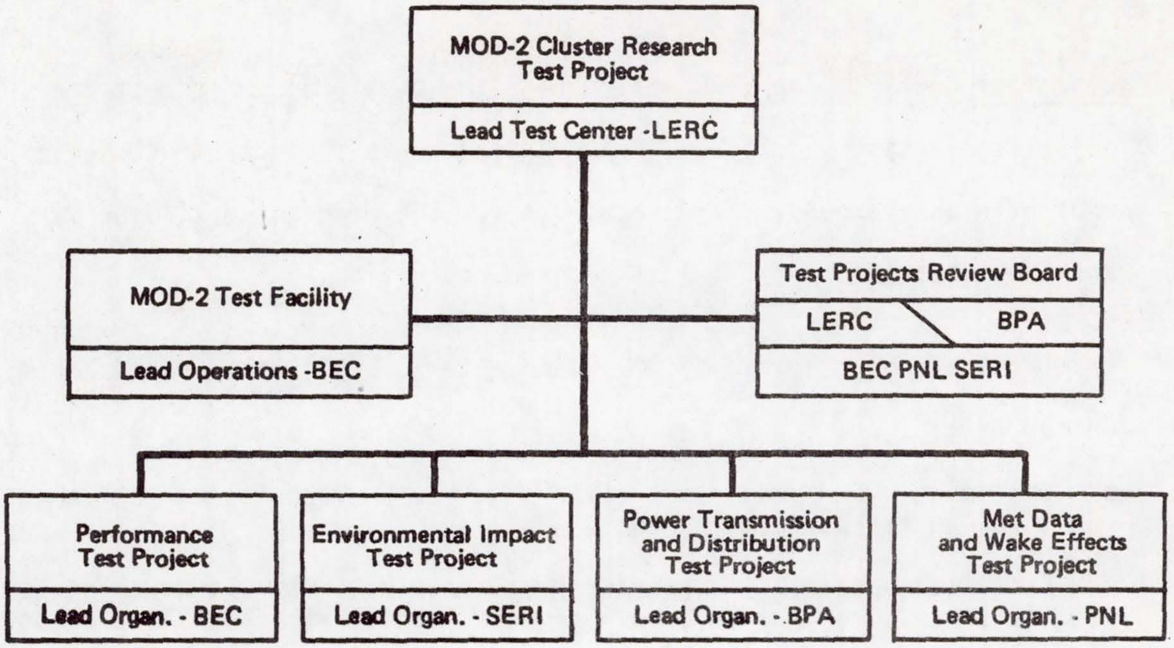

Figure 5.2-1. Management Structure

5.3.1 Lead Test Center - The LeRC will manage the test program to meet the objectives established by DOE Headquarters. This includes the development of plans, schedules and resources for DOE Headquarters' approval and the integration of all test program activities.

Under guidelines provided by DOE Headquarters, LeRC, as the Lead Test Center will:

- o Implement DOE Headquarters policy and review lead test organizations's resource requirements.
- o Establish specific program and project objectives, elements, goals, milestones, and resource requirements jointly with Lead Test Organizations.
- o Prepare implementation and overall program plans jointly with Lead Test Organizations.
- o Establish interface working relationships between the Lead Test Organization and future participating organizations and integrate and coordinate activities.
- o Review Lead Test Organization's annual operating plan to ensure compatibility with scheduled research testing.
- o Implement and manage approved specific test projects at the Lead Test Organization.
- o Establish control responsibilities for specific test projects jointly with Lead Test Organization.
- o Develop and implement an assessment process for evaluating program status and future requirements.
- o Review program progress and provide adequate and timely reporting and documentation to DOE Headquarters.
- o Assume responsibility for program success.
- o Furnish management of and provide resources to the Test Facility Operations Contractor.

5.3.2 Lead Test Organization - The responsibility for all lead test organizations are defined as follows:

- o Implement DOE Headquarters policy.
- o Establish specific test project objectives, elements, goals, milestones, and resource requirements jointly with the LeRC Wind energy Project Office (WEPO).
- o Prepare specific test project plans and annual operating plans.
- o Implement and manage approved specific test projects.
- o Establish and approve changes in test project activities within control thresholds and delegated authorities.
- o Furnish reports to the LeRC Wind Energy Project Office and DOE Headquarters on status, progress, and problems and participate in review meetings and workshops.
- o Provide public and private sector technical liaison with the LeRC Wind Energy Project Office.
- o Assume responsibility for specific test project success.
- o Provide all non-machine related experimental support.

5.3.3 Test Project Review Board - As part of the management structure, a MOD-2 Test Projects Review Board (TPRB) has been formed and is composed of representatives of LeRC, BPA, BEC, Battelle PNL and SERI. The TPRB is jointly chaired by LeRC and BPA. The TPRB shall review detailed test plans, schedules, and procedures associated with the testing of the MOD-2 Cluster. The Test Facility Operations Contractor (BEC) shall document all of the TPRB's recommendations, etc. for submittal to the LeRC and the BPA project officers for approval.

The primary purpose of the TPRB will be to plan and manage the testing of the MOD-2 Cluster. Specific responsibilities shall be:

- o Ensure coordination of DOE Wind Energy Systems MOD-2 test program/facility.
- o Review and approve test project plans submitted by the Lead Test Project Organizations.
- o Ensure dissemination of all test results, analyses, and other relevant data, information and findings.
- o Ensure security and safety of the test facility.
- o Ensure cost effective utilization of instrumentation, data acquisition/reduction facilities.
- o Provide status reports of periodic review meetings.
- o Establish priorities/schedules of test activities.

5.3.4 The MOD-2 contractor, BEC, shall provide the test facility operations under direct management by the Lead Test Center. The primary purpose of this task shall be to provide necessary test operations for support of the various test projects planned by the Lead Test Organizations

Specific responsibilities will be:

- o Provide test facility protection/safety per section 7.5.
- o Provide test operations support including operations of the wind turbines.
- o Provide dissemination of all test data, results, analyses, etc. to LeRC and the Lead Test Organizations.
- o Provide daily log of test operations.
- o Provide non-routine maintenance of the cluster machines.
- o Prepare weekly, semiannual/annual reports on test operations.

6.0 TEST FACILITY

6.1 Site

The Goodnoe Hills Wind Turbine Site is located approximately 15 miles east of Goldendale, Washington on a 2,600 ft. ridge overlooking the Columbia River. Fig. 3.1-1 shows a map of the district. Access is by hard paved road east from Goldendale (Collins Avenue) or from State Highway 8 which leaves U.S. Highway 97 approximately 3 miles south of Goldendale. The hard paved road changes to a gravel road approximately 2 miles from the site. State Highway 8 has a bridge with a limit of 8 tons approximately a mile from US 97.

A Site Plot Map is shown in Fig. 6.1-1. The spacings and relative placements of the three WTS's is such that they are approximately 5, 7 and 10 rotor diameters from each other for examination of wake effects. Table 6.1-1 shows the distances between major site features and their altitudes above sea level. Entrance to the site is on the north side of the road 200 yds west of the visitors' center.

The site office area and parking area, maintained by BEC, is located on the left side of the road 200 yds from the main entrance and opposite the Goodnoe Hills substation. All visitors are required to check in at the BEC office trailer where hard hats are available for site visits. A public information visitors center is located just off Highway 8, opposite WTS #1.

6.2 Test Support

Test support of the facility consists of the on-site capability to support the operation and maintenance of the wind turbine cluster, the Goodnoe Hills substation, the meteorological tower measurements, and the safety and security of the facility.

Table 6.1-1

Distances between major site features at Goodnoe Hills
(All Measurements in Feet)

UNIT	#1	#2	#3	BPA TWR #2	PNL TWR #1	Base Elev Above Sea Level
#1	-	2014	3046	2693	645	2622
#2	2014	-	1505	991	1726	2574
#3	3046	1505	-	523	2504	2568
BPA TWR	2693	991	523	-	2213	2577
PNL TWR	645	1726	2504	2213	-	2624

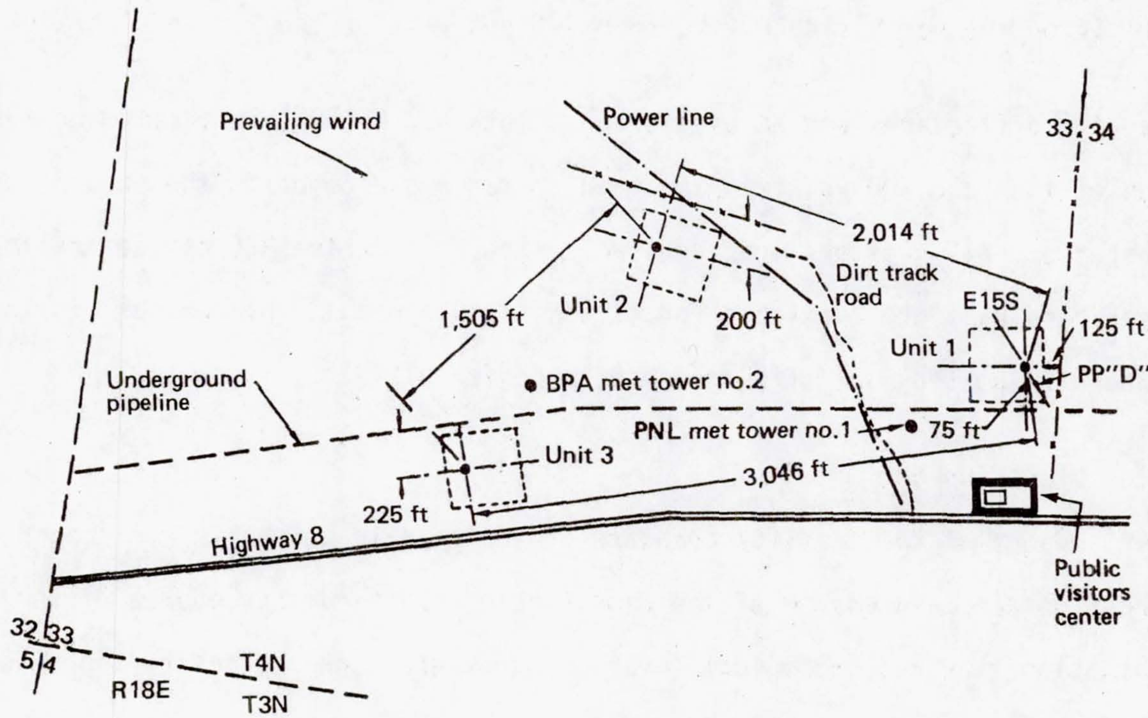

Figure 6.1-1. Goodnoe Hills Site Location Plan

Research testing of the wind turbines will be controlled by BEC who will provide a qualified test operator to operate each required wind turbine in accordance with approved plans for test and procedures. Additional test crew will be available as agreed upon in the test plan. Normal maintenance and minor unscheduled maintenance will be performed by BPA who will utilize operational and maintenance procedures for troubleshooting and repair of a unit. Operational spares will be utilized, as required, for this activity. Major unscheduled maintenance will be the responsibility of BEC subject to NASA/LeRC approval and funding.

During research testing, BEC will notify BPA or the appropriate dispatcher when synchronization is about to occur and when the generator(s) are off-line.

Normal test activities will not require any personnel or manned operation at the Goodnoe Hills Substation. For special tests that do require test personnel at the sub-station, BPA will provide those personnel. All maintenance activities at the substation will be performed by BPA and coordinated with the BEC Site Manager when an interruption of utility power is necessary.

A description of the BPA meteorological tower data system is found in Section 6.3. No manned operations are needed for this system except for periodic retrieval of hard data and normal maintenance for which BPA are responsible.

A description of the PNL meteorological tower data system is found in Sec. 6.3. No manned operations are needed for this system except for normal maintenance, for which PNL are responsible.

When the test configuration requires special permits or approvals, BPA shall secure all necessary leases, zoning changes, building permits, FAA recommendations and other approvals required in time to meet the schedule for this project.

Any state and local environmental impact assessments, if required, shall be the responsibility of the BPA. The federal environmental assessment will be provided by the DOE.

6.3 Data Systems

The nature of the testing of the MOD-2 cluster will sometimes require simultaneous recording of instrumentation on all three machines as well as met tower data. The MOD-2 intersite data system was designed, installed and checked out to accomplish this objective. The data collection center for this system is housed in a 3 by 4.5 meter (10 by 15 foot) building adjacent to WTS 2. Operation of the data center was initiated in April, 1981, and the capability is provided to record and display data from the three wind turbines and the two met towers. In addition to recording analog tapes for data analysis, the data center also houses two computers for formatting data to be sent to BPA and the Battelle Pacific Northwest Laboratory (PNL). Strip chart recorders, a line printer, and a CRT present real time data displays to enable test control. A patch panel is included to permit data access for organizations requesting test data. To facilitate post test processing, all of the data is recorded on a single tape recorder with a common time base. Figure 6.3-1 is a block diagram of the intersite data system. The actual data collected from the three wind turbines and the two met towers are described below.

Engineering data is collected on each wind turbine using the Engineering Instrumentation System (EIS) designed and installed as part of the NASA data system used on all NASA large wind turbines. This system employs one FM multiplexer mounted on the rotating low speed shaft and one FM multiplexer mounted on the nacelle wall to multiplex a total of 64 channels at any one time. A total of 80 transducers are available on each machine and up to 40 may

be selected for real time transmission to the data center from WTS #1 and WTS #3, and up to 64 from WTS #2. Tables 6.3-1, 6.3-2 and 6.3-3 list the measurements available on each WTS and the meteorological towers. During standard data collection (versus a special test requiring a modified data mode), BPA receives 11 engineering measurements from each machine, and PNL receives 6. Table 6.3-4 shows the "Standard" set of data recorded by BEC, BPA and PNL. The data system at each WTS is capable of 40 hertz response. Figure 6.3-2 is a block diagram showing the Engineering Instrumentation System (EIS) installed on each WTS. A data rack at the tower base can be configured to transmit up to 40 selected WTS measurement channels to the data center. The indicated "calibrate" function enables hi/low calibration (e.g., shunt calibration of strain gage channels) of all EIS channels from the tower base.

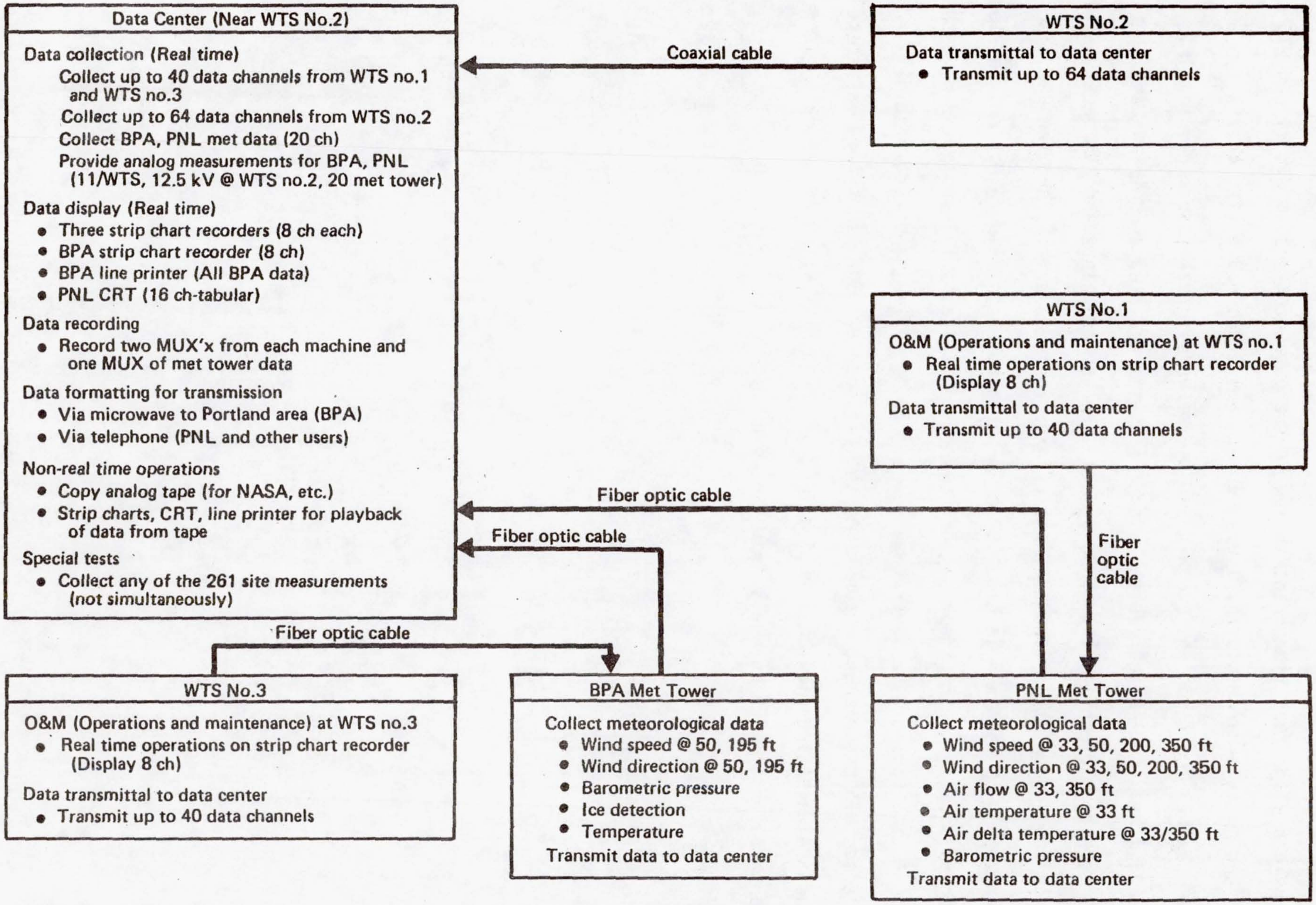

Figure 6.3-1. Intersite Data System Block Diagram

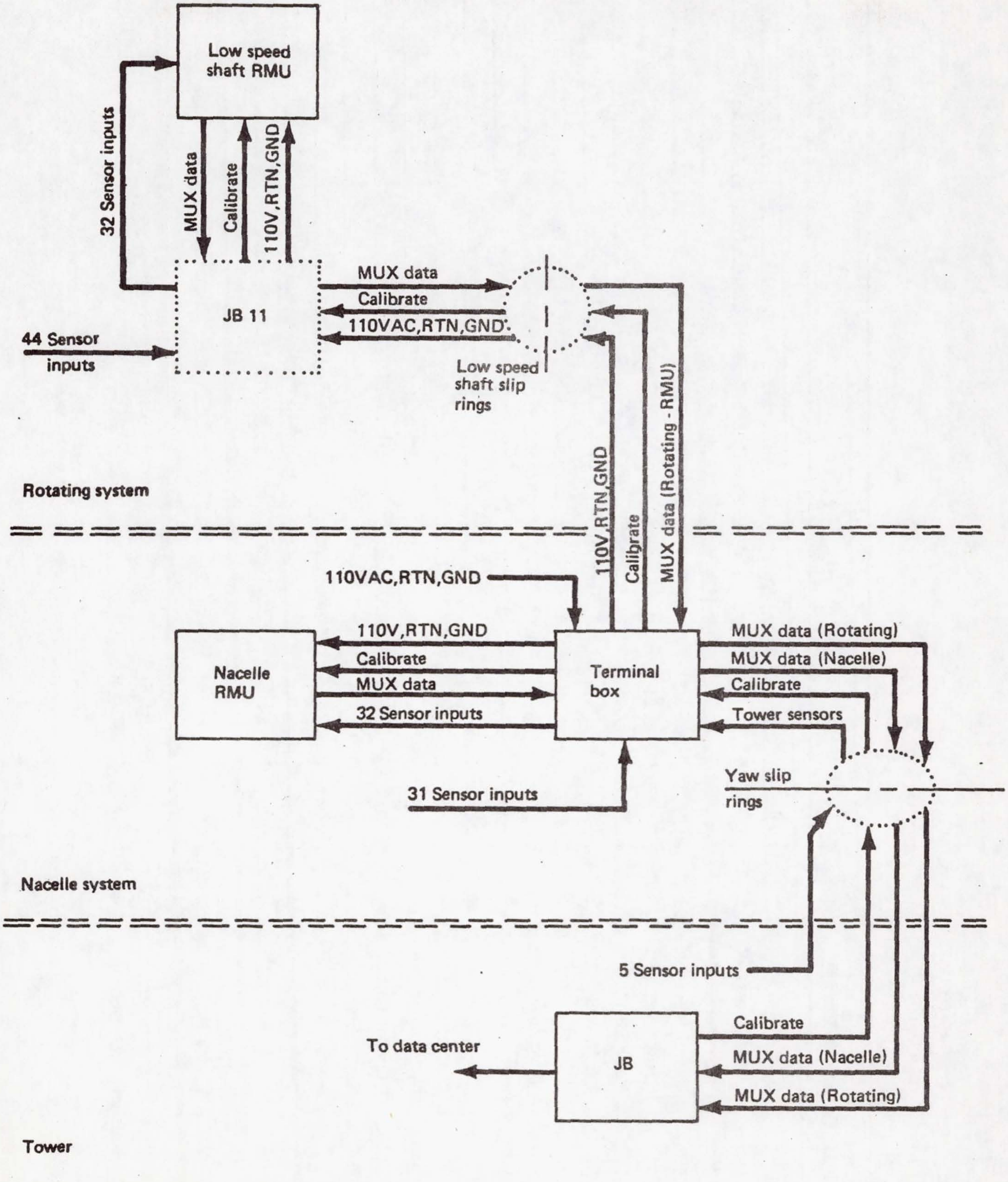

Figure 6.3-2. EIS (Engineering Instrumentation System)

LINE ITEM	MEASUREMENT NUMBER 5	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
1	01MX01	Flapwise Moment, STA 370, Blade 1	± 3.4 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	6
2	01MX02	Chordwise Moment, STA 370 "	± 4 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	6
3	01MX03	Flapwise Moment, STA 1164 "	± 1.1 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	6
4	01MX04	Chordwise Moment, STA 1164 "	± 1.1 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-0 -500BL-350 (4)	6
5	01MX05	Flapwise Moment, STA 1562 "	± 1.3 E4 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-0 -500BL-350 (4)	6
6	01MX06	Chordwise Moment, STA 1562 "	± 1.2 E5 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	6
7	01PX01	Pitch Actuator Pressure 1 1 "	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
8	01PX02	Pitch Actuator Pressure 2 2 "	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
9	01SX01	Critical Strain, STA 372 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
10	01SX02	Critical Strain, STA 622 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
11	01SX03-1	Critical Strain, Fwd. STA 882 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
12	01SX03-2	Critical Strain Aft, STA 882 "	± 500 µE	SG Bridge (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
13	02MX01	Flapwise Moment, STA 370, Blade 2	± 3.4 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
14	02MX02	Chordwise Moment, STA 370 "	± 4 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
15	02MX03	Flapwise Moment, STA 1164 "	± 1.1 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
16	02MX04	Chordwise Moment, STA 1164 "	± 1.1 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
	02PX01	Pitch Actuator Pressure 1 1 3 "	-232 to +3768 psig	Pressure Transducer	Genisco SP100-5000-S-0.5 (5000 psig)	
	02PX02	Pitch Actuator Pressure 2 2 3 "	-232 to +3768 psig	Pressure Transducer	Genisco SP100-5000-S-0.5 (5000 psig)	
17	02SX01	SACS 4, STA 1207, UPPER OUTSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
18	02SX02	SACS 4, STA 1207, UPPER INSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
19	02SX03	SACS 4, STA 1207, LOWER INSIDE	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	

NOTES:
1 Pressure increase tends to decrease pitch
2 Pressure increase tends to increase pitch
3 Redundant measurement (unconnected)
4 SACS (Spindle Area Critical Strain)

5 For WTS #1 X = 1
WTS #2 X = 2
WTS #3 X = 3

6 Nominal Value - Will vary per machine

TABLE 6.3-1 ENGINEERING MEASUREMENT LIST (WTS ROTATING SYSTEM)

LINE ITEM	MEASUREMENT NUMBER 5	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
20	02SX04	SACS 4 3, STA 1207, LOWER OUTSIDE Blade 2	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
	02SX05	SACS 4 3, STA 1207, UPPER OUTSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
	02SX06	SACS 4 3, STA 1207, UPPER INSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
	02SX07	SACS 4 3, STA 1207, LOWER INSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
	02SX08	SACS 4 3, STA 1207, LOWER OUTSIDE "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
21	03DX01	Position, Teeter Angle "	± 10.68 Degrees	Linear Potentiometer	Bourns 5184 Linear Potentiometer	
22	03MX01	Flapwise Moment, STA 100, Blade 1	± 4.2 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
23	03MX02	Chordwise Moment, STA 100 "	± 3.2 E6 Ft-Lbs	SG Bridge (4 Act Arm)	Micro Meas WA-06-500BL-350 (4)	6
24	03SX01	Critical Strain 1, STA 003 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
25	03SX02	Critical Strain 2, STA 003 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
26	03SX03	Critical strain 1, STA 102 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
27	03SX04	Critical Strain 2, STA 102 "	± 500 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
28	03SX05	Critical Strain 1, Teeter Trunnion "	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-250WT-350 (1)	
29	03SX06	Critical Strain 2, Teeter Trunnion "	± 195.1 µE	SG (Single Gage)	Same Gage as 03SX05	
30	03SX07	Critical Strain 3, Teeter Trunnion "	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-250WT-350 (1)	
31	03SX08	Critical Strain 4, Teeter Trunnion "	± 195.1 µE	SG (Single Gage)	Same Gage as 03SX07	
32	03SX09	TSCS 7, Trailing Edge & Blade 1 side	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
33	03SX10	TSCS 7, Leading Edge & Blade 2 side	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
34	03SX11	TSCS 7, Trailing Edge & Blade 2 side	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
35	03SX12	TSCS 7, Leading Edge & Blade 1 side	± 195.1 µE	SG (Single Gage)	Micro Meas WA-06-500BL-350 (1)	
36	03TX01	Elastomeric Bearing Temperature	-38.34 to +177.26°F	Resistance Thermometer	Burns 10819-1 Res. Thermometer	

NOTES:
1. Pressure increase tends to decrease pitch
2. Pressure increase tends to increase pitch
3. Redundant measurement (unconnected)
4. SACS (Spindle Area Critical Strain)
5. For WTS #1 X = 1; WTS #2 X = 2; WTS #3 X = 3
6. Nominal Value - Will vary per machine
7. TSCS (Teeter Stop Critical Strain

TABLE 6.3-1 ENGINEERING MEASUREMENT LIST (WTS ROTATING SYSTEM)

LINE ITEM	MEASUREMENT NUMBER 5	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
37	05MX01	Moment 1, Quill Shaft	± 2.71 E4 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	
38	05MX02	Moment 2, Quill Shaft	± 2.71 E4 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	
39	05UX01	Torque, Quill Shaft	-0.4 E6 to 1.6 E6 Ft-Lb	SG Bridge (4 Act Arms)	Micro Meas WA-06-250TL-350 (2)	6
40	09PX01	Pressure, Pitch Accumulator #1	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
41	09PX02	Pressure, Pitch Accumulator #2	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
42	09PX03	Pressure, Pitch Accumulator #3	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
43	09PX04	Pressure, Pitch Hydraulic Oil	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psig)	
44	09TX01	Temperature, Pitch Hydraulic Oil	-38.34 to +177.26°F	Resistance Thermometer	Burns WSP1A1-5 1/2-3A Res. Thermometer	

5 For WTS #1 X = 1
WTS #2 X = 2
WTS #3 X = 3

6 Nominal Value - Will vary per machine

TABLE 6.3-1 ENGINEERING MEASUREMENT LIST (WTS ROTATING SYSTEM)

LINE ITEM	MEASUREMENT NUMBER 5	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
1	04AX01	Vibration, Lo Sp Shaft Fwd. X Axis	± 0.2g	Accelerometer	CEC4-205-0001-1 Accel (1g)	
2	04AX02	Vibration, Lo Sp.Shaft Fwd. Y Axis	± 0.2g	Accelerometer	CEC4-205-0001-1 Accel (1g)	
3	04AX03	Vibration, Lo Sp Shaft Fwd, Z Axis	± 0.2g	Accelerometer	CEC4-205-0001-1 Accel (1g)	
4	04AX04	Vibration, Lo Sp Shaft Aft. X Axis	± 0.2g	Accelerometer	CEC4-205-0001-1 Accel (1g)	
5	04DX01	Position, Rotor	0 to 360 Degrees	Angular Potentiometer	Bourns 6657 Rotary Potentiometer	
6	04TX01	Temperature, Fwd Lo Sp Shaft Brg.	-38.34 to +177.26°F	Resistance Thermom.	Burns 9858-1 Res. Thermometer	
7	04TX02	Temperature, Aft Lo Sp Shaft Brg.	-38.34 to +177.26°F	Resistance Thermom.	Burns 9858-1 Res. Thermometer	
8	06AX01	Vibration, Gear Box Aft, X Axis	± 0.5g	Accelerometer	CEC4-205-001-2.5 Accel (2.5g)	
9	06AX02	Vibration Gear Box Aft, Y Axis	± 0.5g	Accelerometer	CEC4-205-001-2.5 Accel (2.5g)	
10	06PX01	Pressure, Gear Box Oil	-9.28 to +150.72 psig	Pressure Transducer	Genisco SP100-200-S-0.5 (200 psig)	
11	06TX01	Temperature, Gear Box Oil	-38.34 to +177.26°F	Resistance Thermom.	Burns WSP1A1-6 1/2-3A-Res. Thermometer	
12	07AX01	Vibration, Generator Input, X Axis	± 0.5g	Accelerometer	CEC4-205-001-2.5 Accel (2.5g)	
13	07IX01	Amperes, Generator	-160 to +640 Amps	Current Transducer	RIS CCC-1B-C5-EO-X-F60-ZO-A2-G1	Phase B
14	07IX02	Amperes, Generator Field	0 to 5 Amps	Current Transducer	RIS CCC-1B-C5-EO-X-F60-ZO-A2-G1	
15	07FX01	Phase Angle, Generator	± 20 Degrees	Phase Angle Transducer	RIS PFN-1B-60-P1-EO-C5-X-F60-WO-ZO-A1-G1	Phase A to Phase B
16	07NX01	Power Delivered to Utility	-1000 to +4000 KW	Power Transducer	RIS PCE-20-P1-EO-C5-X-F60-WO-ZO-A2-G1	Phase A + Phase B + Phase C
17	07VX01	Volts, Generator	0 to 3000 Volts	Voltage Transducer	RIS VCC-1B-P1-EO-X-F60-ZO-AZ-G1	Phase C Line to Neutral Voltage
18	08DX01	Position, Nacelle	0 to 360 Degrees	Angular Potentiometer	Bourns 6657 Rotary Potentiometer	
19	08TX01	Temperature, Inside Nacelle	-38.34 to +177.26°F	Resistance Thermometer	Burns 9986-1 Res.Thermometer	
20	08TX02	Temperature, Outside Air	-38.34 to +177.26°F	Resistance Thermometer	Burns WSPOG1-2 1/2-3B Res. Thermometer	
21	10PX01	Pressure, Yaw Hydraulic Oil	-232 to +3768 psig	Pressure Transducer	Genisco SP 100-5000-S-0.5 (5000 psi)	

5 For WTS #1 X = 1
WTS #2 X = 2
WTS #3 X = 3

TABLE 6.3-2 ENGINEERING MEASUREMENT LIST (WTS STATIONARY SYSTEM)

LINE ITEM	MEASUREMENT NUMBER [5]	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
22	11CX01	Contrl. Sys. Pitch 1 Command Error	± 10 Degrees/Sec.	Control System	NCU (Nacelle Cntrl Unit) A3 Drawer	
23	11CX02	Contrl. Sys. Pitch 2 Command Error	± 10 Degrees/Sec.	Control System	NCU A3 Drawer	
24	11DX01	Contrl. Sys. Blade 1 Pitch Pos.	-10 to +105 Degrees	Control System	NCU A3 Drawer	
25	11DX02	Contrl. Sys. Blade 2 Pitch Pos.	-10 to +105 Degrees	Control System	NCU A3 Drawer	
26	11NX01	Contrl. Sys. Generator Output	-1000 to +4000 KW	Control System	NCU A3 Drawer	Phase A + Phase B + Phase C
27	11RX01	Contrl. Sys. Rotor RPM	0 to 20.97 RPM	Control System	NCU A3 Drawer	
28	11WX01	Contrl. Sys. Wind Speed, Sensor 1	0 to 50.2 MPH	Control System	NCU A3 Drawer	
29	11WX02	Contrl. Sys. Wind Speed, Sensor 2	0 to 50.2 MPH	Control System	NCU A3 Drawer	
30	11WX03	Contrl. Sys. Wind Rel Dir.Sensor 1	0 to 360 Degrees	Control System	NCU A3 Drawer	
31	11WX04	Contrl. Sys. Wind Rel Dir.Sensor 2	0 to 360 Degrees	Control System	NCU A3 Drawer	
32	12AX01	Acceleration, Top of Tower, Y Axis	± 0.2g	Accelerometer	CEC 4-205-0001-1 Accel (1g)	
33	12AX01	Acceleration, Top of Tower, Z Axis	± 0.2g	Accelerometer	CEC 4-205-0001-1 Accel (1g)	
34	12UX01	Torque, Tower, Sta 600 X Axis	± 2.35 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-250TL-350 (2)	
35	12MX01	Bend Mom, Tower, Sta 600 Y Axis	± 7.62 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	
36	12MX02	Bend Mom, Tower, Sta 600 Z Axis	± 7.62 E6 Ft-Lbs	SG Bridge (4 Act Arms)	Micro Meas WA-06-500BL-350 (4)	

[5] For WTS #1 X = 1
WTS #2 X = 2
WTS #3 X = 3

TABLE 6.3-2 ENGINEERING MEASUREMENT LIST (WTS STATIONARY SYSTEM)

LINE ITEM	MEASUREMENT NUMBER	MEASUREMENT	RANGE	TYPE OF SENSOR OR DATA SOURCE	SENSOR	NOTES
1	14WD11	PNL Wind Direction at 33 ft.	0 to 360 Deg CW from N		Climet	
2	14WD21	PNL Wind Direction at 50 ft.	0 to 360 Deg CW from N		Climatronics	
3	14WD31	PNL Wind Direction at 200 ft.	0 to 360 Deg CW from N		Climet	
4	14WD41	PNL Wind Direction at 350 ft.	0 to 360 Deg CW from N		Climatronics	
5	14WS11	PNL Wind Speed at 33 ft.	0 to 100 mph		Climet	
6	14WS21	PNL Wind Speed at 50 ft.	0 to 111.8 mph		Climatronics	
7	14WS31	PNL Wind Speed at 200 ft.	0 to 100 mph		Climet	
8	14WS41	PNL Wind Speed at 350 ft.	0 to 111.8 mph		Climatronics	
9	14DT41	PNL Delta Temp at 33/350 ft.	-5 to +15°C			
10	14AT11	PNL Air Temp at 33 ft.	-30 to +50°C			
11	14BP01	PNL Barometer Pressure	875 to 975 mb			
12	15ID21	BPA Ice Detector	Present/Not Present	Magneto-Strictive Oscillator	Rosemount, Model 871CB1	
13	15BP01	BPA Barometric Pressure	822.8 to 1066.6 mb	Bellows/Resistor	Climatronics 100099/100091	
14	15WD31	BPA Wind Direction at 195 ft.	0 to 360 Deg CW from N	Potentiometer	Belfort, Type L 5-120-HD	
15	15WD21	BPA Wind Direction at 50 ft.	0 to 360 Deg CW from N	Potentiometer	Belfort, Type L 5-120-HD	
16	15WS31	BPA Wind Speed at 195 ft.	0 to 94.634 mph	DC Generator	Belfort, Type L 5-120-HD	
17	15WS21	BPA Wind Speed at 50 ft.	0 to 94.634 mph	DC Generator	Belfort, Type L 5-120-HD	
18	15AT21	BPA Air Temp at 50 ft.	-30 to +120°F	Resistor	Climatronics 100093/100087	

TABLE 6.3-3 ENGINEERING MEASUREMENT LIST (MET TOWERS)

Meas No.	Measurement	Standard Data Available BEC	BPA	PNL
08D101	WTS #1 Nacelle Position	x	x	x
11N101	WTS #1 Generator Pwr Output	x	x	x
11W101	WTS #1 Wind Speed, Sensor 1	x	x	x
11W102	WTS #1 Wind Speed, Sensor 2	x	x	x
11W103	WTS #1 Wind Dir. Sensor 1	x	x	x
11W104	WTS #1 Wind Dir. Sensor 2	x	x	x
11R101	WTS #1 Rotor RPM	x	x	
07I101	WTS #1 Field Current	x	x	
07F101	WTS #1 Phase Angle	x	x	
07N101	WTS #1 Power to Utility	x	x	
07V101	WTS #1 Generator Volts	x	x	
08D201	WTS #2 Nacelle Position	x	x	x
11N201	WTS #2 Generator Pwr Output	x	x	x
11W201	WTS #2 Wind Speed Sensor 1	x	x	x
11W202	WTS #2 Wind Speed Sensor 2	x	x	x
11W203	WTS #2 Wind Dir. Sensor 1	x	x	x
11W204	WTS #2 Wind Dir. Sensor 2	x	x	x
11R201	WTS #2 Rotor RPM	x	x	
07I201	WTS #2 Field Current	x	x	
07F201	WTS #2 Phase Angle	x	x	
07N201	WTS #2 Power to Utility	x	x	
07V201	WTS #2 Generator Volts	x	x	
08D301	WTS #3 Nacelle Position	x	x	x
11N301	WTS #3 Generator Pwr Output	x	x	x
11W301	WTS #3 Wind Speed, Sensor 1	x	x	x
11W302	WTS #3 Wind Speed Sensor 2	x	x	x
11W303	WTS #3 Wind Dir. Sensor 1	x	x	x
11W304	WTS #3 Wind Dir. Sensor 2	x	x	x
11R301	WTS #3 Rotor RPM	x	x	
07I301	WTS #3 Field Current	x	x	
07F301	WTS #3 Phase Angle	x	x	
07N301	WTS #3 Power to Utility	x	x	
07V301	WTS #3 Generator Volts	x	x	

Meas No.	Measurement	Standard Data Available BEC	BPA	PNL
14WD11	PNL Wind Dir at 33 ft.	x	x	x
14WD21	PNL Wind Dir at 50 ft.		x	x
14WD31	PNL Wind Dir at 200 ft.	x	x	x
14WD41	PNL Wind Dir at 350 ft.	x	x	x
14WS11	PNL Wind Speed at 33 ft.	x	x	x
14WS21	PNL Wind Speed at 50 ft.	x	x	x
14WS31	PNL Wind Speed at 200 ft.	x	x	x
14WS41	PNL Wind Speed at 350 ft.	x	x	x
14DT41	PNL Delta Temp 33/350 ft.	x	x	x
14AT11	PNL Air Temp at 33 ft.	x	x	x
14BP01	PNL Barometric Pressure	x	x	x
15ID21	BPA Ice Detector		x	x
15BP01	BPA Barometric Pressure	x	x	x
15WD31	BPA Wind Direction of 195 ft.	x	x	x
15WS21	BPA Wind Direction at 50 ft.	x	x	x
15WS31	BPA Wind Speed at 195 ft.	x	x	x
15WS21	BPA Wind Speed at 50 ft.	x	x	x
15AT21	BPA Air Temp at 50 ft.	x	x	x
-	12.5 KV Bus Volts		x	

TABLE 6.3-4 STANDARD DATA SET

Met data are also transmitted from the two met towers to the data center. Transmission of all data from WTS #1 and WTS #3 to the data center is accomplished using fiber optics to preclude the possibility of electrical interference from the adjacent buried power output cables which are located a few inches from the FM (analog) data cables.

6.4 Communications

For research testing, communication will usually use hand held UHF walkie-talkie radios. Normally during testing, a radio is located at each of the operating wind turbines, one at the data center and one at the office trailer. Additional radios can be located at other special test facilities as required. A temporary installed intercom hard-wired system can be used for communication between several locations close to a particular facility.

For field operation BPA has installed a Dial Automatic Telephone Switching (DATS) circuit to the site to provide party line service via the BPA Microwave Radio Communication System. Handsets are located at each wind turbine, the data center, the sub-station and the radio station. DATS provides telephone service between the site and BPA Dittmer Control Center in Vancouver, Washington, and other parts of the BPA system. A commercial phone line is also available at each wind turbine, the sub-station and the office trailer.

7.0 TEST METHODS

7.1 Test Planning

Before developing a test plan, a study of available information from the MOD-2 cluster is recommended. Section 3.0 and 6.0 of this document provide data on the MOD-2 system, the method of normal operation and the facilities available at the Goodnoe Hills site. Section 5.0 provides information on the roles and responsibilities of the major participants in the Program.

Other important data that provides guidance for test planning is the history of wind performance at the site. Figure 7.0-1 shows the expected monthly windspeed distribution at Goodnoe Hills for both cut-in wind speed (14 mph) and above rated wind speed (27 mph). Wind directional frequency for the period 9/5/80 to 8/6/81 is shown in Fig. 7.0-2 and daily variation of wind speed by hour averaged over the same period, is shown in Fig 7.0-3.

Support information such as performance of the utility grid, simulation of the MOD-2 system results of similar tests on other wind turbine systems, etc, may be obtained through the appropriate members of the TPRB.

It is important to note that budgeted costs for operation of the cluster can be minimized by tailoring the test to conform to "normal" operation at the site as much as possible. This includes consideration of such factors as:

a) keep manned operations during an 8 hour shift/5 days per week.

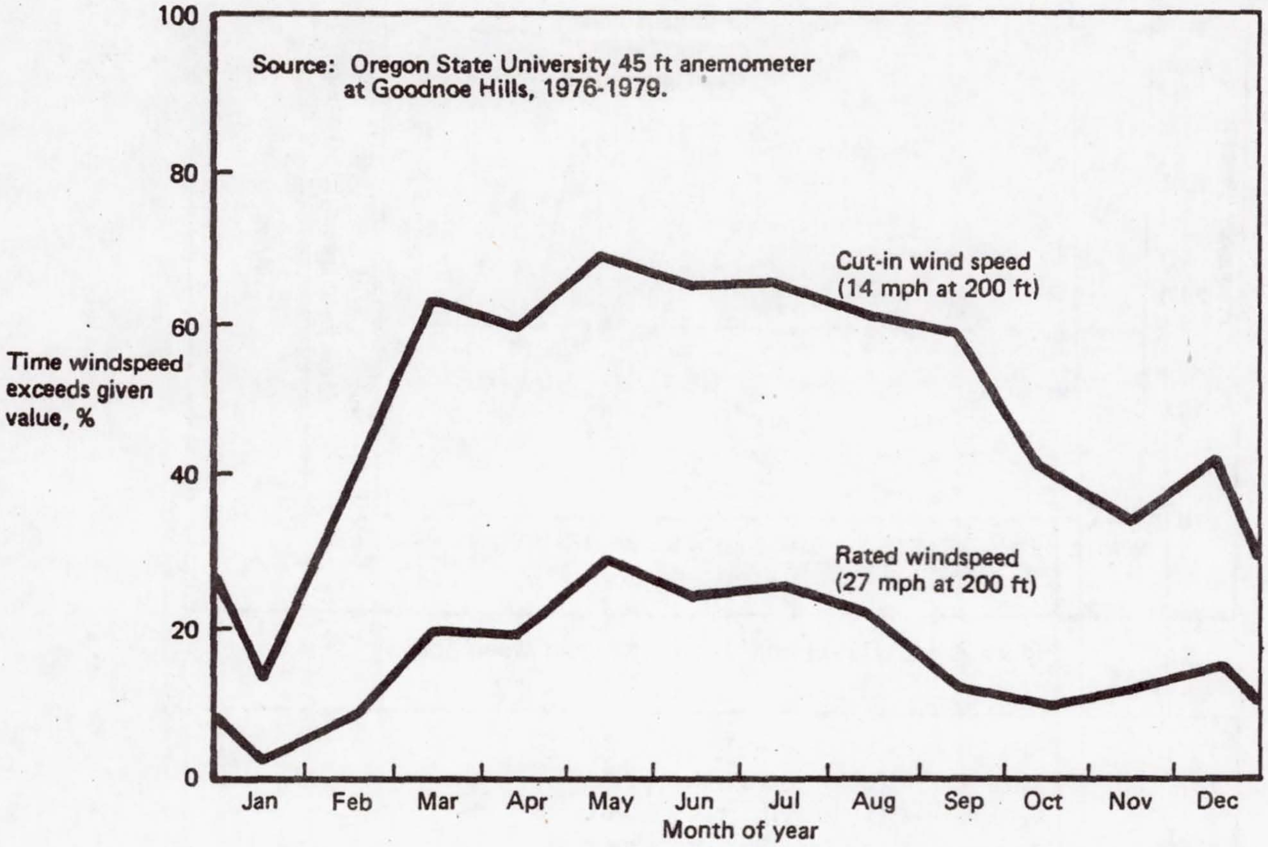

Figure 7.0-1. Expected Monthly Windspeed Distribution at Goodnoe Hills

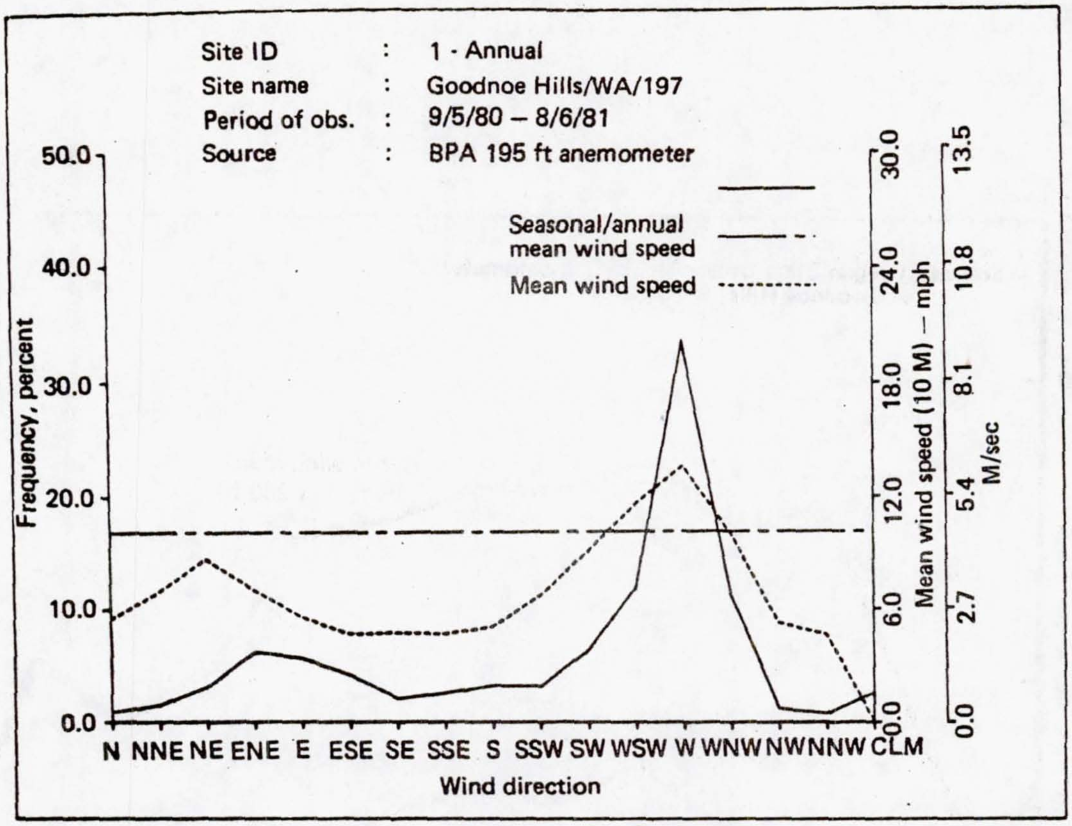

Figure 7.0-2. Directional Frequency and Mean Speed

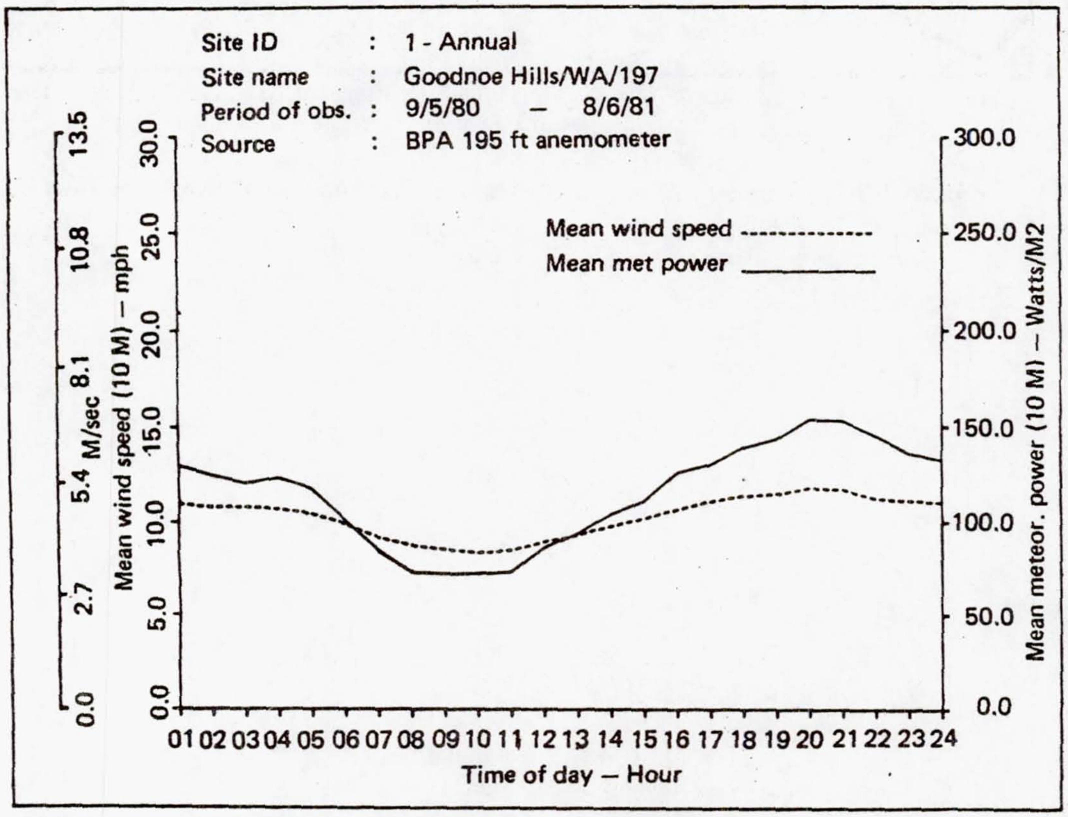

Figure 7.0-3. Daily Variation in Mean Speed and Power

b) test data acquisition satisfied by standard data set.

c) WTS configuration unmodified.

d) minimize data processing requests, e.g., use BEC, BPA and PNL reports.

7.1.1 Test Plan

An important aspect of the management of this test project plan is effective planning, execution and reporting. Accordingly, test plans shall be written to define the work required to accomplish discrete tests (e.g., Performance, Environmental Impact), in support of a test activity. These test plans shall be generated by the designated test managers of the cognizant Lead Test Project Organizations. The format of these respective test plans shall be as follows:

Objective(s)

- o Defines briefly the overall goal(s) of the test activities as well as identifying an approach as to how the goal(s) will be attained through successful completion of individual tasks.

Test Conditions

- o Lists for each test the parameters and range for which the test hardware is to be run.
- o Defines the environmental conditions to which the research package or subsystem is to be exposed during pre-test, test and post-test operations for each test point.

Facility Requirements

- o Identifies and briefly describes the facility in which the test is to be conducted.
- o Identifies any test-unique interface problems.

Facility Requirements (Continued)

- o Describes and provides design criteria, sketches or other suitable information on any known modifications.
- o Identifies data acquisition system to be used.
- o Describes the test set-up, with suitable sketches, drawings, photos or other illustrations.
- o Defines each individual subsystem in test set-up and provides adequate design criteria where fabrications and installations are required.
- o Identifies all known major parts to be produced and installed for the test set-up.

Operational Impact

- o Lists measurements to be made of wind turbine or special modifications/test set-up supporting test equipment by:

  measurement (sensing element or sensor)
  location
  recording
  accuracy
  frequency response

- o Supplies detailed requirements for recording, handling, processing and reducing the data.

Test Matrix

- o Presents a detailed schedule of:

  periodic meetings to review progress in carrying out Test Plan.
  design/fabrication/installation of test set-up
  minor modification of facility
  procurement of hardware
  installation of research package
  test-readiness review
  checkout runs
  test runs
  other

Data Reduction and Analysis

- o Describe planned data analysis methods, statistical techniques
- o Describe expected output and results

Documentation

- o Specifies report requirements, including periodic reviews and progress reports on technical progress, costs and schedule.

- o Specifies distribution of Test Plan reports and other documents.

7.1.2 Test Procedures

Test procedures will be prepared by the Test Facility Operations Contractor (BEC) based on the test plans identified in Vol. II of this document. These can use extracts from the MOD-2 Operation & Maintenance Handbook or provide step-by-step procedures for unique test activity. They will include definition of the configuration of the Wind Turbine System, the data system, the particular environmental conditions to be met, the prerequisites to be satisfied prior to conducting the test, the specific condition at which test data is taken, criteria for when it can be determined that test conduct is complete and instructions for where data are to be delivered. Particular emphasis will be placed in identifying potentially hazardous operations and conditions where safety requirements need to be noted.

The test procedure will be reviewed and approved by the cognizant lead test project organization prior to start of test to verify that the objectives of the test plan will be met.

7.1.3 Plan of Test

A "Plan of Test" will be prepared by the Test Facility Operations Contractor (BEC) and will provide an abbreviated sequence of the tests to be run listing all the test conditions (by paragraph number from the test procedure) to be accomplished. When several tests can be conducted concurrently, the "Plan of

Test" will provide the necessary integration planning of the testing sequence.

Normally the "Plan of Test" will be one or two page plan prepared by the test conductor at the site and updated prior to each pre-test meeting.

7.2 Test Conduct

The test will be run in the most cost effective and expeditious manner possible with consideration for normal testing methods at the site and consistent with strict adherence to safety and security requirements. Figure 7.2-1 shows a typical test activity flow. The testing will be directed by the cognizant Lead Test Project Organization and conducted by the Test Facility Operations Contractor (BEC) with support from appropriate organizations. All testing will be performed to approved test procedures.

Prior to the start of a major test phase, a test readiness review will be held to determine if all systems and participants are ready, and will include a detailed review of the test procedure. Following the completion of a major test phase, a post test review will be held to verify that the test requirements have been completed and that the appropriate data has been collected.

Failures of operational equipment will be handled through normal channels unless specified otherwise in the Test Plan. Failures of non-WTS equipment (test unique) will be handled by the responsible organization for that equipment.

A daily test operations report will be prepared by BEC to summarize the previous day's activities and provide test progress visibility.

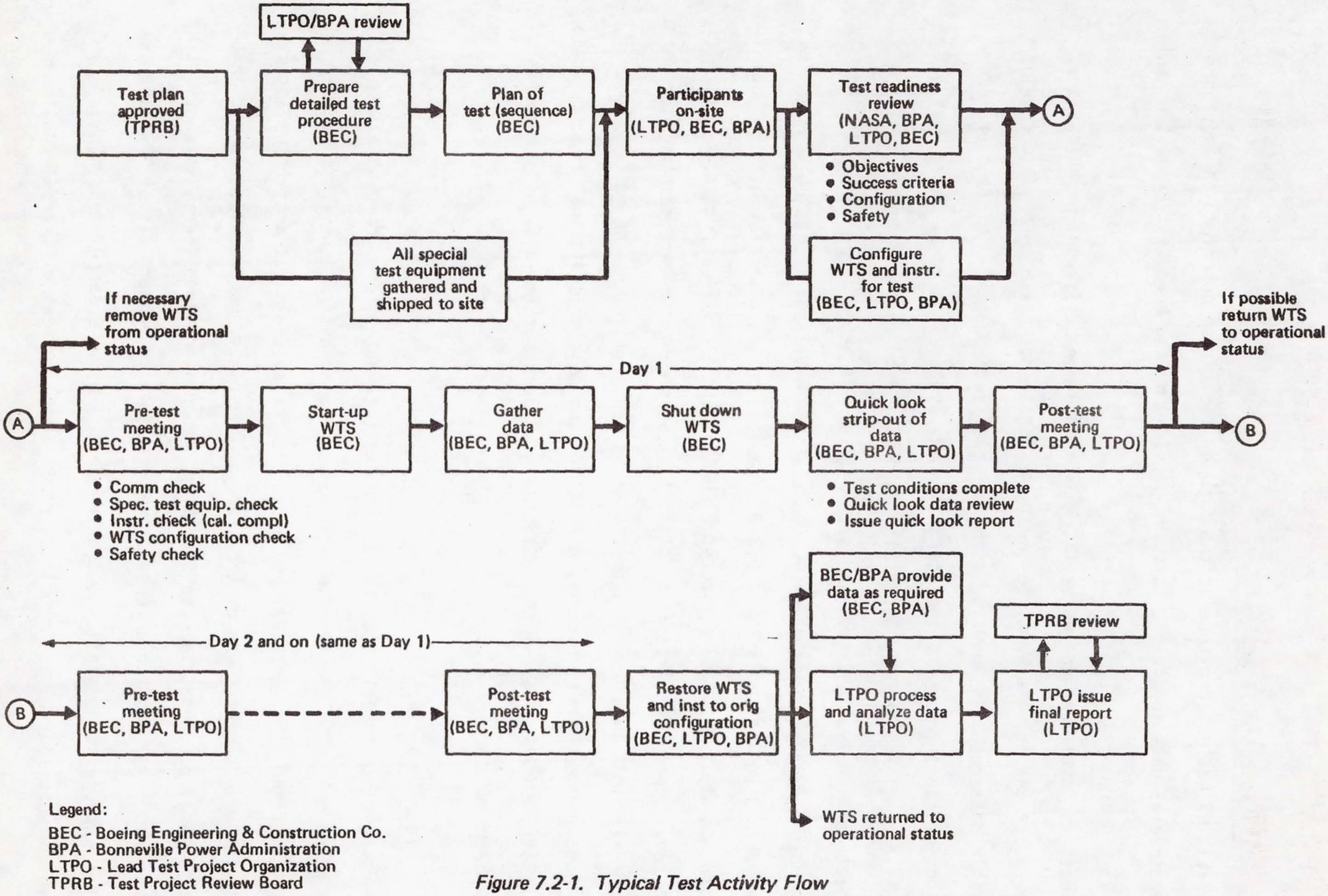

Figure 7.2-1. Typical Test Activity Flow

7.3 Data Reduction & Analysis

Data will be collected either at the site by the system described in Section 6.3 or by special data acquisition systems provided by the Lead Test Project Organization.

Requests for data are handled by the TPRB. Since many different organizations, both public and private, will be involved, no attempt has been made to develop specific data requests. However each test plan must contain a minimum of information for configuring and operating the data system (see para. 7.1). During normal operations, the Goodnoe Hills cluster will be operable continuously subject to wind availability, and data will always be recorded on the 11 BPA (includes 6 PNL) WTS parameters listed in Table 6.3-1 and -2, as well as the met tower data also listed in Table 6.3-3. The data collected by PNL will be published monthly. The data collected by BPA is used for BPA reports. In general, data requirements for "standard data" (11 measurements on each machine plus met tower data) will be relatively easily satisfied. Even for standard data however, the data requester must normally budget for the cost of additional reports, data printouts, etc. Suggestions for minimizing the costs related to data requests are discussed in para 7.1.

7.4 Test Reporting

Reporting of test activities falls into two categories; one for general reporting of normal activities at the site (e.g. wind condition, normal operation results of the wind turbines, etc.) and one for special test activities associated with unique operations of the wind turbines (e.g. performance evaluation of the turbines under special configuration or operating conditions, wake effect tests etc.). All published reports are available to members of the TPRB and other appropriate organizations on request. In accordance with DOE Wind Energy Technology Division policy, normal peer reviews will be accomplished on test reports prior to publication.

7.4.1 General Test Reporting

BEC issues a weekly report summarizing the operation of the wind turbines at Goodnoe Hills (see Figures 7.4-1 and 7.4-2). This report uses a similar format to that reported for wind turbines at Clayton, New Mexico and Oahu, Hawaii. Battelle PNL issues a monthly report on the wind sensor performance at three (3) elevations (50,200 and 350 ft.) at Goodnoe Hills. This report includes the following information.

(1) Monthly means and standard deviations

(2) Maximum wind speed

(3) Wind speed and direction vs. time of day

(4) Frequency distribution of wind speed

(5) Wind speed persistence frequency

Site logs and activity reports are also kept but not normally published.

Upon request from the LeRC, BPA shall make available certain data on the operations and costs and on experiences with the wind turbines operating in the utility system. This may at times be in the form of oral presentations and/or written papers.

Papers presented at energy or industry organization conferences will be encouraged; however, Lead Test Project Organizations shall coordinate any reports or papers relative to the wind turbines with the LeRC Wind Energy Project Office.

7.4.2 Special Test Reports

The tests planned under this program plan will be reported by the Lead Test Project organization as identified in this plan. When appropriate, interim reports will be issued by the Lead Test Project Organization indicating the

MOD 2
WIND TURBINE SYSTEM

Weekly Operations Report

WTS No. ____ Week Ending ______________

Sync. time (Hours) ________ Plant factor ______________________

MWHRS produced __________ Availability ______________________

Average MW ______________ Adjusted availability* ______________

Modifications/Special tests:

Maintenance summary:

Remarks:

*Deletes affect of modifications and special tests

Reported by: __________________________

Date: ______________________

Figure 7.4-1. Weekly Operations Report Form

Period	Sync hours		MW hours		Average MW		Plant factor ①		WTS avail ②		Adjusted WTS avail ③		Remarks
	Period	Year to date	Period	Year to date	Period	Year to date	Period	Year to date	Period	Year to date	Period	Year to date	
Total													

① Plant factor = $\dfrac{\text{kWh generated/period}}{\text{2,500 kW X (P-ST-MOD)}}$

② $\dfrac{\text{P - (ST + MOD + Maint)}}{\text{P}}$

③ $\dfrac{\text{(P - ST - MOD) - (Maint)}}{\text{(P - ST - MOD)}}$

MOD = Modification time
Maint = Maintenance time
P = Period time
ST = Special test time

Figure 7.4-2. Performance Summary Form

progress of the test to date and the results obtained. Final reports will be released through the TPRB.

7.5 Safety and Security

Normal site safety and security will be provided by BEC as identified in MOD-2 Safety Plan for Site Installation and Test Activities (Boeing Document D277-10201-1). The Site Safety Engineer (BEC) and BPA will review any planned potentially hazardous operations to ensure the procedures provide for adequate safety to personnel and equipment. BPA facilities are subject to BPA safety rules and regulations. Safety and first aid equipment is available at the site and is maintained by BEC. During test operations access to the site and individual wind turbines will be authorized and controlled by BEC.

8.0 TEST PLAN SUMMARY

Detailed Research Test Plans for the MOD-2 Cluster Research Test Program are to be found in Vol. II of this document. Table 8.0-1 below is a summary of the primary objectives of the presently planned tests and the Lead Test Project Organization involved. The following paragraphs provide additional information on each of the planned tests.

a) Performance Testing (para. 8.1)
b) System Verification and Improvement (para. 8.2)
c) Environmental Impact (para. 8.3)
d) Power Transmission and Distribution (para. 8.4)
e) Machine Dynamics and Structural Analysis (para. 8.5)
f) Meteorological Data (para. 8.6)
g) Wake Effects (para. 8.7)
h) Cluster Array Analysis (Para. 8.8)
i) Array Maintenance Evaluation (Para. 8.9)
j) Advanced Concepts Verifications (para. 8.10)

This is available as preliminary information only and this section will only be updated when warranted by other changes to this document; for current planning, see Vol. II.

TABLE 8.0-1
Summary of Primary Test Objectives

Test Title	Primary Objective
Baseline System Performance Test (BEC)	To evaluate the performance achieved (or achieveable) by the baseline configuration. This will be measured in terms of power output as a function of wind speed and the energy produced as a fraction of the energy available in the actual wind environments experienced.
High Wind Cut-out Speed Test (BEC)	To determine the maximum wind speed at which the MOD-2 may be operated, and what modifications are required to permit the MOD-2 to operate at wind speeds above 45 mph when the wind spectrum includes significant time in the above 45 mph wind speed regime.
Power Output Limit Test (BEC)	(1) Evaluate capability of rotor and drive shafts to operate at higher torque. (2) Establish limiting values of torque. (3) Develop a recommended control concept to operate at the optimum power output limit.
Low Wind Start-up Shutdown (BEC)	(1) Reduce number of start/stop cycles. (2) Increase annual net energy production.
Pitch Setting Refinement (BEC)	(1) Adjust the start-up algorithms to assure maximum acceleration through 10 rpm. (2) Evaluate algorithm changes to minimize the time to synchronization. (3) Adjust pitch settings at below rated power to optimize power output.

Table 8.0-1 (Continued)

Test Title	Primary Objective
Yaw Control Refinement (BEC)	(1) Reduce yaw angle excursions (2) Reduce time spent at excessive yaw angles. (3) Reduce the magnitude and frequency of cyclic loading associated with excessive yaw angles (4) Reduce number of shutdowns from excessive yaw angles (5) Establish optimum system with consideration of the duty cycle of the yaw drive system
Wake Structure Measurements (PNL)	To measure and visually document the structure of the MOD-2 wake as a function of position in the time-average wake under a broad class of ambient atmospheric conditions.
Wake Effects Performance (PNL)	To determine the extent of wake effects on the performance of a downwind wind turbine at separations of 5, 7 and 10 rotor diameter and at a variety of ambient atmospheric conditions.
Acoustic Emission of a Single MOD-2 Wind Turbine (SERI)	To document the characteristics of the acoustic noise produced by the isolated rotor of a single MOD-2 turbine under a range of operating conditions; i.e., wind speeds (cut-in to cut-out) and inflow turbulence regimes, and to compare the results with similar measurements taken near other turbine designs as well as previous surveys of the MOD-2.
Acoustic Emissions of Multiple MOD-2 Wind Turbines (SERI)	The documentation of the acoustic noise produced by downwind elements of a cluster of three MOD-2 wind turbines at three separate spacings for comparison with the emissions associated with a single turbine operating alone.

Table 8.0-1 (Continued)

Test Title	Primary Objective
Television Interference Tests (SERI)	(1) To determine the electrical scattering area of the MOD-2 turbine blade in order to validate the University of Michigan scattering model for this machine. (2) To determine the areal extent of the forward and back scattering regions for a single MOD-2 turbine and compare these measurements with the predictions of the University of Michigan Model. (3) To examine any effects of multiple scattering due to the operation of a cluster of large wind turbines.
Voltage Regulations on the 69KV Feeder Line with Single and Multi Wind Turbine Systems (BPA)	To obtain data and analyze the electrical impacts to the utilities' distribution system and quality of power delivered to the utilities' customers with the WTS voltage regulator operating in both the constant factor mode and constant terminal voltage mode.
Validation of WTS Simulation Model (BPA)	(1) Validate the various models used to simulate the MOD-2 WTS. (2) Verify the operation and response of the WTS's to disturbances impacting the electrical power system.
Wind Turbine Generator Power Variation Analysis (BPA)	(1) Determine the reliability and statistical characteristics of electrical power derived from wind resources. (2) Derive data from which the influence of wind generator placement, upon overall power production, can be determined. (3) Assess the likelihood of adverse interactions between the power system and the wind generation facility. (4) Provide selected data base for use in evaluating future wind farm deployments.

8.1 Performance Test Plan

8.1.1 Baseline System Performance Measurement

OBJECTIVE: The primary goal of this Baseline System Performance test is to evaluate the performance achieved (or achievable) by the baseline configuration. This will be measured in terms of power output as a function of wind speed and the energy produced as a fraction of the energy available in the actual wind environments experienced.

A secondary objective is to evaluate and compare the calculated performance (kW) versus wind speed against the actual performance achieved at each wind speed.

APPROACH: The basis for evaluating wind speed is the anemometer data from each of the PNL and BPA meteorological towers. The PNL meteorological data from the three elevations will be averaged for two minute periods to provide the baseline wind speed and direction assumed to exist in the rotor disk plane. These data will be processed into periodic (daily, weekly, or monthly) wind frequency distributions. Temperature and barometric pressure recorded from the meteorological towers will be used to correct the atmospheric density. These data will then be combined by $(1/2\rho v^3)$x(disk area) to obtain the total wind energy available (KWH/period) as well as the relationship between Cp versus tip speed. The actual performance of the wind turbine power output as measured by the wattmeter and recorded on magnetic tape will be correlated with the wind power available and expressed as a measure of efficiency.

Actual measured KWH correlation will be adjusted to account for those periods in which the wind turbine is in lockout mode for maintenance or other test reasons.

TEST MATRIX: The evaluation of baseline system performance is essentially a continuous test. The meteorological data will be recorded on a continual basis with the data processed and published monthly. The power and energy output of each turbine is recorded for all the operating periods. Selective periods encompassing various operating wind speeds will be planned in which continuous data sampling and one minute averages will be processed.

8.1.2 High Wind Cutout Speed Tests

The baseline MOD-2 is designed to shutdown when the wind speed at hub height exceeds 45 mph. The collective pitch angle that corresponds to this 45 mph cutout point was determined by design analysis to be 13 degrees. Actual high wind sensing and shutdown control is accomplished by monitoring the average collective pitch (51 second running average) and initiating shutdown when this averaged value exceeds 13 degrees. At some wind sites, a significant increase in annual energy would be achieved by permitting wind turbine operation at higher wind speeds.

Operation at off-wind yaw angles in the high wind speed regimes results in increased rotor teetering motions and

associated higher cyclic loads. At various combinations of wind speed and yaw angle, rotor teeter excursions may be sufficient to cause impacting of the teeter stops.

<u>OBJECTIVE</u>: To evaluate system performance at the high end of the design wind spectrum and examine the effects of increasing the high wind cutout threshold above 45 mph.

Sub-Level Objectives are:

1) To obtain correlation of high wind shutdown point with actual windspeed.
2) Measure critical rotor loads at maximum negative Cp during high wind shutdowns.
3) Evaluate performance of startup algorithms at wind speeds above 45 mph.
4) Evaluate pitch control outer loop stability at wind speeds above 45 mph.
5) Evaluate pitch control inner loop performance in the 15° to 25° blade angle regime at wind speeds above 45 mph.
6) Evaluate the need for an instantaneous high wind cutout threshold (maximum allowable instantaneous blade angle) in addition to the existing 51 second averaging method.
7) Evaluate teeter angles (excursions as a function of wind speed and yaw angles).
8) Evaluate system peak and cyclic loads as a function of wind speed and yaw angles.
9) Evaluate yaw algorithm efficiency in high wind regime.
10) Evaluate ability of yaw drive system to provide control at wind speeds above 45 mph.

APPROACH: This testing will require operating winds in a range starting at above-rated operating mode (28 mph) and extending well above 45 mph, as measured at WTS hub height.

No modifications will be implemented during initial operational evaluation of teeter angles, teeter stop contacts, structural loads, and yaw angles. Initial operational evaluation will require no special equipment and will employ the basic configuration existent at WTS acceptance. This baseline control system has the following characteristics:

1) Shutdown when blade tip angle average over 1 minute exceeds 13 degrees (45 mph wind).
2) Yaw correction at 1/4°/sec when averaged yaw error exceeds ± 7 degrees for 5 minutes, or when averaged yaw error exceeds ± 20 degrees for 30 seconds.
3) Shutdown when averaged yaw error exceeds 20 degrees for 2 minutes.

It is expected that the initial evaluation will indicate desired test-only configuration changes to control system software/firmware for further test and evaluation. Baseline data will be analyzed for conformance to predicted loads, stress levels and margins of safety. These analyses will indicate any requirements for basic control system changes and will also indicate the potential for operating at higher wind speeds.

These changes may involve refinements/variations to pitch and yaw control algorithms, and adjustments to operational limits to permit testing at wind speeds above 45 mph. Operational wind speed limits will be increased incrementally during test up to a potential high wind cutout point of 60 mph.

After concluding the test and evaluation iterations, the following types of software and/or hardware changes may be considered for formal implementation:

1) Change software/firmware to recognize proper pitch angle for shutdown at desired high wind cut-out speed.
2) Change operating pitch control algorithm.
3) Change operating yaw control algorithm.
4) Change shutdown algorithm for excessive yaw.
5) Increase yaw drive motor power.

TEST MATRIX: Testing should commence at the earliest time when sustained high winds are projected to be available. Preliminary definitions of software test patches will be available 30 days after test plan approval and will be updated/refined in consonance with actual testing.

8.1.3 Power Output Limit Test

The MOD-2 gearbox was designed and tested at a torque loading and rpm equivalent to 3750 kW. The MOD-2 generator is rated at 3125KVA at 7,000 ft. altitude. It therefore has capability for a power output of 3125 kW if operated at a power factor of

unity. At lower altitude, the generator is capable of additional power output.The limiting power output of the generator is, in general, a function of internal temperature due to losses. It may be desirble to implement wind turbine power output control based on measured generator temperature.

The factors that limit the power output of the MOD-2, as presently configured, are the structural capabilities of the rotor and drive shafts, and the maximum allowable operating temperature within the generator.

<u>OBJECTIVE</u>: To explore the potential for increasing the maximum power output capability above the current rating of 2,500 kW. This entails:

1) Evaluating the capability of the rotor and drive shafts to operate at higher torque.
2) Establishing limiting values of torque.
3) Examining the temperature characteristics of the generator as a function of power output and ambient environment.
4) Developing a recommended control concept to permit operation at the optimum power output limit.

<u>APPROACH</u>: This testing will require that significant operating time be achieved with winds above 28 mph to operate at rated power.

Initial evaluation will be conducted at rated power of 2500 kW. Following initial evaluation, the operational limits will be incrementally increased, with on-line analyses being

conducted to establish safe limits for the next incremental change.

The initial configuration is the same as during acceptance. Power output is controlled at 2500 kW. The generator is controlled by a power factor controller set at unity power factor.

Initial operational evaluation will require no special equipment or modification to evaluate blade and drive shaft loads and stresses. Strain gauge data, wind speed and directional data will be analyzed to show structural loads correlation with stresses and margins of safety. It is expected that the initial evaluation will indicate desired test-only configuration changes to software/firmware and possibly hardware for continued test and evaluation.

If the initial evaluation shows that adequate structural margins exists, then software/firmware modifications will be implemented to operate and test incrementally at higher values of power output. This will also require adjustment of the AC overcurrent relay in the failsafe system.

Assuming suitable structural margins are found to exist, it may be desirable to propose a control system which utilizes generator winding temperature for limiting control of power output.

TEST MATRIX: Testing should commence during a period of projected steady high winds.

8.1.4 Low Wind Startup/Shutdown

The baseline configuration initiates shutdown when the power output averaged over 51.2 seconds is less than 125 kW. Considerable operating time is lost during startup during these low wind conditions. It is anticipated that many start/stops would be eliminated and that additional annual energy could be achieved by allowing some motoring at wind speeds down to approximately 11 mph.

OBJECTIVE: To evaluate performance and system efficiency at low wind speeds. Specific objectives include examining frequency and duration of startup/shutdown cycling and establishing control settings that optimize system performance versus system reliability.

APPROACH: This testing will require a significant time of operating in winds in the region of 8 to 15 mph. During initial testing, the control algorithms will remain unchanged. Following evaluation, the software/firmware may be modified to allow motoring.

Configuration is the same as during acceptance. This baseline control system has applicable characteristics of:

(1) Shutdown at low wind (approx. 11mph) when a power output is less than 125 kW averaged over 51.2 seconds.

(2) Startup is initiated when accumulated nacelle wind sensor data samples (each sample averaged over 12.8 second period) meet the following criteria: $\sum$(sample-13) >48, with the summation value reset to zero anytime (sample-13) $\leq$ zero.

No modifications will be implemented during initial evaluation of start/stop cycles. Following baseline evaluation, the software/firmware will be modified to allow various levels and time increments of monitoring low power operation.

Initial operational evaluation will require no special equipment. Test-only configuration changes to software/firmware will be implemented to allow motoring or in other ways improve the start-up sequence.

TEST MATRIX: Analysis of the operational data will identify the number of stops at marginally low wind speeds which could be avoided by motoring. The effect of reducing the number of start/stop cycles on fatigue life will be determined. The time from shutdown to resynchronization and the new energy to be gained by motoring will be calculated. Necessary modifications to the test unit will be made to allow motoring. Actual performance will then be compared to the control unit.

8.1.5 Pitch Setting Refinement

Below rated power, the control system operates at two values of fixed pitch with rate damping. The values selected may not be optimum. Revised and/or additional settings may optimize power output at below rated power.

During start-up the pitch settings have been programmed as a function of wind speed and rpm to provide maximum acceleration to 10 rpm. Above 10 rpm the pitch settings are controlled as a function of rotor speed ramp until synchronization is achieved at 17.5 rpm.

OBJECTIVES:

(1) Evaluate the start-up algorithms to determine control settings that maximize acceleration through 10 rpm.

(2) Evaluate algorithm changes to minimize the time to synchronization.

(3) Evaluate pitch settings at below rated power to optimize power output.

APPROACH: This testing will require a significant time of operations in winds below 28 mph with power outputs over the range of 125 kW to 2500 kW. Several values of pitch settings for below rated power will be implemented.

Configuration will be the same as at acceptance. This baseline control system has characteristics of:

(1) Initiate start-up with pitch to appropriate breakaway angle for existing wind speed.

(2) Pitch settings controlled as a function of rpm and startup wind speed until achieving 5 rpm.

(3) Above 5 rpm the control algorithm uses a look-up table of blade angle for maximum rpm acceleration as a function of startup wind speed and rpm until achieving 10 rpm.

(4) Between 10 rpm and 17.4 rpm, the control algorithm uses a second lookup table to accomplish a smooth transition from maximum acceleration to zero acceleration, again as a function of rpm and startup wind speed.

(5) Above 17.4 rpm the control algorithms utilize hub rate error (17.5 minus rpm) and integral hub rate error to achieve synchronization.

(6) During operation at below rated power, the control system operates at two fixed values of pitch. For increasing winds, the blade pitch is +5 degrees until changeover to +3 degrees at 1100 kW. For decreasing winds, the pitch is +3 degrees until changeover to +5 degrees at 900 kW.

(7) Above rated power, the pitch settings continuously vary to maintain constant power output in the presence of variable winds

<u>TEST MATRIX</u>: Initial analysis will be made to assure that startup algorithms are appropriate to achieve startup without false starts. Changes will be recommended if appropriate. Analysis of operational data will compare power output as a function of the various pitch settings. Optimum values will be established.

Initial evaluation of startup and below rated power operation will be conducted prior to any modifications. If found necessary, the startup algorithms and look-up table values will be adjusted.

Following initial evaluation, the software/firmware will be incrementally modified to improve power output at below rated power. Consequently this area will require test-only software/firmware.

8.1.6 Yaw Control Refinement

The yaw control is based on time averaging of yaw values as determined by the nacelle wind sensors. Any refinements in control algorithms which will reduce the time spent at yaw angles will improve power output by the third power of the cosine of the yaw angle.

OBJECTIVES: The primary objective is to increase the annual energy captured.

Sublevel objectives are:

(1) Evaluate yaw angle excursions

(2) Study time spent at various angles of yaw

(3) Explore means of reducing the magnitude and frequency of cyclic loading associated with excessive yaw angles.

(4) Reduce number of shutdowns from excessive yaw angles

(5) Establish optimum system with consideration of the duty cycle of the yaw drive system.

APPROACH: This testing will require significant time of operation under all operating wind conditions with emphasis on low wind startups. Initial evaluation will require no special equipment. Test only configuration changes to software/firmware will be implemented to improve the yaw algorithm.

Configuration will be as at acceptance. This baseline control system has characteristics of:

(1) During startup, the yaw pumps are turned on and yaw correction initiated after the wind speed averaging algorithm determines the winds are correct for operation.

(2) The yaw rate is 1/4 degree per second.

(3) Startup will not occur unless the yaw error is reduced to less than 20 degrees within 2 minutes.

(4) During operation, the control algorithm initiates yaw correction if the yaw error exceeds 7 degrees for a period of 5 min. Yaw correction is also initiated if the yaw error exceeds 20 degrees for 30 seconds.
Shutdown is initiated if the yaw angle exceeds 20 degrees for more than 2 minutes.

TEST MATRIX: Following baseline evaluation, the software/firmware will be modified (possibly several increments) with periods of operational evaluation between increments of change.
Analysis of data will identify:

(1) Time lost during startups due to yaw

(2) Number of stops due to excessive yaw

(3) Yaw drive duty cycles

(4) Energy losses due to off-wind operation

Calculations will assess the improvement potential for changes to the yaw control algorithm. After modification of one test unit, the operational efficiency improvement can be assessed against the other two unmodified units.

8.2 System Verification and Improvement Test Plan

Individual test plans for this section will be prepared and submitted at a later date. Tentative candidate tasks for this section are listed below. Additional candidates may be identified as the test and evaluation program progresses.

8.2.1 System Response Evaluation

8.2.2 Maintenance Evaluation

8.2.3 Teeter Brake Release Variation

8.2.4 Yaw Hydraulic Evaluation

8.2.5 Emergency Shutdown Study

8.2.6 Generation Excitation Control

8.2.7 System Simplification Evaluation

8.2.8 Power Control Function

8.2.9 Wind Sensor Improvement Study

8.2.10 Gearbox Oil Cooling Evaluation

8.2.11 One-Tip Shutdown Evaluation

8.3 Environmental Impact of MOD-2 Turbines

8.3.1 Acoustic Emissions Associated with the Operation of a Single MOD-2 Wind Turbine

An on-going study of acoustic noise from large wind turbines by SERI has shown the community annoyance associated with turbine operations has been related to the degree of phase coherence in the emitted acoustic pressure spectrum, particularly at low and sub audible frequencies where harmonic coupling to nearby residential structures can occur. Figure 8.3-1 summarizes a typical acoustical spectrum associated with a large wind turbine and indicates the characteristics and frequency ranges of the dominant noise sources. The ultimate cause of the high levels of acoustic energy in the sub audible and low frequency range (5-100 Hz) and in the so-called "spectral hump" (800-1200 Hz) is the non-uniform loading of the turbine rotor brought about by natural inflow turbulence and turbulence generated by the support structure itself and rotor wakes from upstream machines. It is expected that the dominant unsteady sources for the MOD-2 will be the turbulent structure of the natural flow (which is probably site dependent to a great extent) and from rotor wakes of upstream installations. Previous measurements of the MOD-2 noise have shown no great tendency for impulsive behavior similar to that found with the MOD-1, but high levels of audible energy were found (800-1200 Hz) which can be heard for distances up to several thousand feet downwind. All previous surveys have been conducted during daylight hours, whereas surveys of other

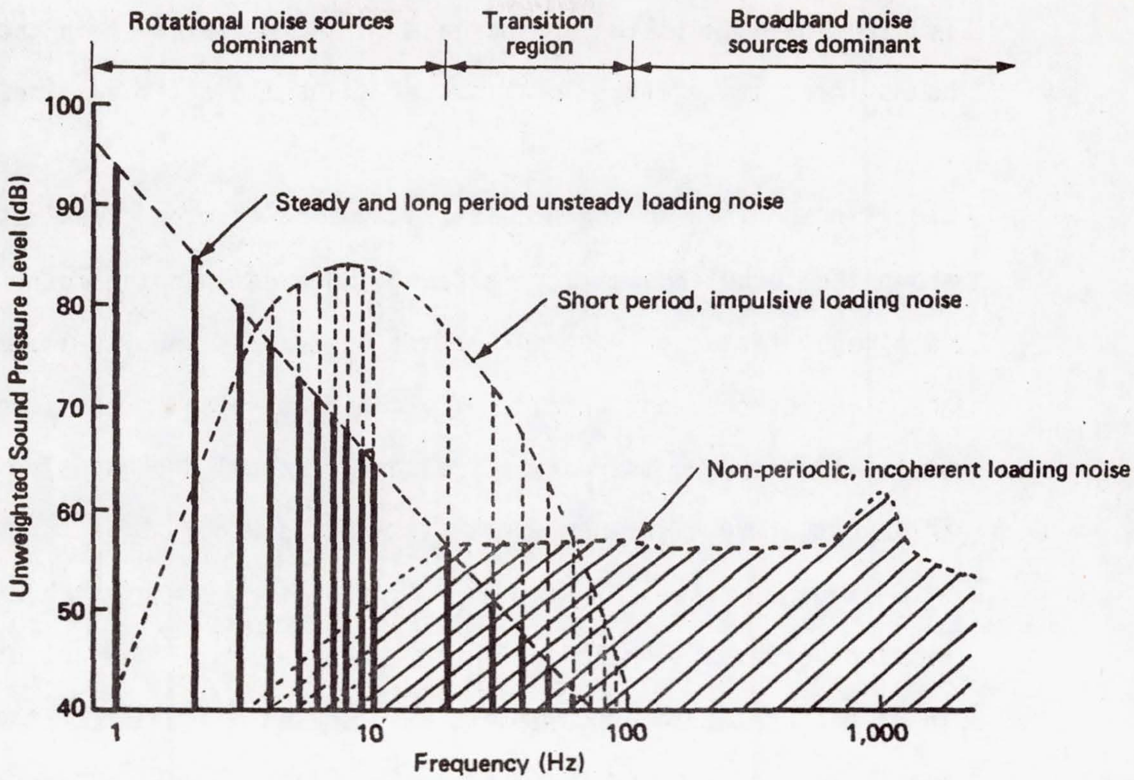

Figure 8.3-1. Wind Turbine Noise Characteristics

machines have indicated an increase in the noise level in the hours immediately after local sunset and again after sunrise.

Experience gained in the acoustic surveying of other turbines has shown the turbulence structure being ingested into the rotor disk is a major factor in determining the observed sound levels and the level of coherent or partially coherent noise in the important 5-100 Hz band (structural resonance range) and may also play an important role in the levels of high frequency noise (800-1200 Hz) observed. Wind tunnel and full-scale atmospheric tests have shown turbulence length scales are quite important in affecting the acoustic levels with scales the order of the mean blade chord being the most influential. Thus, in assessing the acoustic performance of a given wind turbine design, it is necessary to measure the emissions under a range of atmospheric conditions in which widely varying turbulent flow structures can be expected to exist.

OBJECTIVE: To document the characteristics of the acoustic noise produced by the isolated rotor of a single MOD-2 turbine under a range of operating conditions; i.e., wind speeds (cut-in to cut-out) and inflow turbulence regimes, and to compare the results with similar measurements taken near other turbine designs as well as previous background surveys of the Mod-2.

APPROACH: The objectives will be accomplished through the use of very wide band acoustic recording equipment located at ground level and at hub height through the use of a tethered balloon and wide band FM telemetry. Pairs of microphones will be employed on the ground to allow coherent detection of the turbine acoustic signal in the presence of wind-induced background noise. To assess the location of the noise source responsible for the higher frequency sounds, a microphone will be mounted at approximately the 80-100 ft. level above the ground on one or more of the support towers. To determine the characteristics of the inflow turbulence on the observed acoustic levels, a hot-film, constant-temperature anemometer will be alternated with the balloon-borne microphone. Simultaneous recording of the inflow turbulence spectrum and the resulting acoustical spectrum then can then be achieved by using multi-channel, FM magnetic recording. In support of the acoustic and turbulence measure-ments, it will be necessary to parallel record a number of dc signals representing machine operating parameters such as blade angle, generator power output, rotor position, and yaw angle. Meteorological support from the two existing towers will also be required as detailed below. Permission to mount a rugged, wide-band velocity sensor at a height equivalent to the 80% span position on a blade while in the vertical position will also be requested.

It is desired to acquire acoustic and turbulence data over a range of operating conditions including windspeeds from cut-in to

cut-out and under various states of natural, turbulent inflow. The thermodynamic stability of the layer of air within the rotor disk has a major influence on the characteristics of the turbulence found. It is proposed to collect as much data as possible in the three normally found turbulence regimes; i.e., unstable, stable-turbulent, and stable-laminar, with the greatest emphasis on the stable-turbulent regime since it is in this situation the most discrete turbulence structure is found.

TEST MATRIX: It is proposed to use either WTS #1 or WTS #2 for the single machine evaluations. These machines allow the greatest degree of flexibility for both the tethered balloon upstream and the array of microphones on the downwind side. Operations will begin at approximately 1600 hrs. local time and continue until approximately 0100 hrs. in order to track the development of the surface layer as it transitions from the daytime convective layer to the nocturnal. Three periods of turbine shutdown of a 15 minute duration will be required during the data collection period to establish local acoustical background levels. No special activities in the actual operation of the turbine are required; i.e., fixed power levels, fixed blade angle, etc. The weather must be dry, the instrumentation cannot be satisfactorily operated in precipitation. Similarly, the unpaved surface conditions must also be dry and able to withstand the weight of vehicles without seriously breaking the surface. The remaining turbines are not to be operating during this time.

The balloon-borne platform will be operated no closer than 1-1/2 rotor diameters (450 ft.) ahead of the turbine and in flight level winds not above about 12 m/s (25 mph) depending on turbulence levels. Microphones will be placed at a number of selected distances from the tower base on azimuths dependent on the wind direction and rotor orientation a combination of cables and FM telemetry links will be used to transfer this information to the survey van for recording.

8.3.2 Acoustic Emissions Associated with the Operation of Multiple MOD-2 Wind Turbines

OBJECTIVE: The documentation of the acoustic noise radiated by downwind elements of a cluster of three MOD-2 wind turbines at three separate spacings and compared with the emissions associated with a single turbine operating alone (see Section 8.3.1).

APPROACH: As explained in Section 8.3.1, the levels of coherent and partially coherent acoustic radiation will be monitored and compared with single turbine operation under a range of atmospheric operating conditions. The technique will be to cycle the upwind turbine on/off at regular intervals (on 60 minutes, off 15 minutes) and compare the resulting acoustic emission spectra and pressure-time signatures. The three spacings (5, 7, and 10 rotor diameters) will be used under a range of atmospheric conditions including both stable and unstable flows. A tethered balloon-borne microphone or hot film anemometer will be flown no

closer than 1 1/2 rotor diameters upstream of the downwind turbine to further assess the levels of unsteady loading through acoustic means and to determine the characteristics of the turbulent structure entering the turbine rotor disk.

TEST MATRIX: The choice of which pair of turbines will be used will be a function of the mean wind direction. WTS #3 (upwind) and WTS #2 (downwind) will be used when the mean wind direction is 220°; WTS #2 and #3 when the direction is 253°; and WTS #3 and #1 when the direction is 280°. These correspond to the 5, 10, and 7 diameter spacings respectively. Surface acoustic measurements will only be taken at the 1 1/2 rotor diameter distance along the turbine axis and in the rotor plane. The operating period will be the same as for the single turbine experiment; i.e., approximately 1600-0100 hours local time.

8.3.3 Television Interference Tests

OBJECTIVES:

(1) To determine the electrical scattering area of the MOD-2 turbine blade in order to validate the University of Michigan scattering model for this machine

(2) To determine the areal extent of the forward and back scattering regions for a single MOD-2 turbine and compare these measurements with the predictions of the University of Michigan Model

(3) To examine any effects of multiple scattering due to the operation of a cluster of large wind turbines.

APPROACH: To perform both static and dynamic tests to determine the ambient signal levels and effects of turbine operation respectively on received television signals in various locations surrounding the Goodnoe Hills Site. Ambient signal strengths will also be measured at the top and base of each of the three turbines with the turbines stationary. The effects of any multiple scattering will be evaluated from at least two remote sites: one in the forward and one in the backward scattering regions. Television signals from the Portland stations will be used as excitation sources for the experiments.

TEST MATRIX: It will be necessary to have all three turbines shut down during the measurements of ambient field strengths at the base and at the nacelle heights as well as during certain periods when remote data is to be taken. All measurments can be taken during normal working hours, no special atmospheric conditions are needed. For the dynamic tests, a wind sufficient to enable the rotors to turn is all that is necessary.

Static Tests: Tests will be conducted at particular remote sites and using one specific turbine with the others kept stationary with their blades locked in a specific position and oriented towards a suitable direction. With the receiving antenna main-beam directed towards the turbine under test and then at the desired TV transmitter, the received signal vs. time will be obtained under the following conditions: (a) the turbine blade locked in a vertical position and the nacelle yawed through a

complete circle (360°), and (b) the turbine blade locked in a horizontal position and the machine yawed through 360°.

Dynamic Tests: At each remote site, the following sets of data will be collected on all available TV channels: (a) received signal vs. antenna pointing direction; (b) received signal vs. time with the antenna pointed at a specific turbine; and (c) the received signal vs. time with the antenna pointed at the TV transmitter. These data will be obtained under the following conditions using the given sequence of operating turbines: (a) Turbines #1, #2 and #3 stationary; (b) Turbines #1 and #2 operating, #3 stationary, and (c) all three turbines operating. The sequence of operation may be altered if necessary.

8.4 Power Transmission and Distribution Test Plan

8.4.1 Voltage Regulations on the 69-kV Feeder Line with Single and Multiwind Turbine Systems

The generator voltage regulator of the MOD-2 Wind Turbine System will initially be operated at unity power factor for all generator loads. The generator voltage regulator can also be operated for constant voltage at the generator terminals. Voltage and other electrical data will be obtained to determine if excessive voltage variation becomes a problem to customers on the 69 kV line when the MOD-2 WTS are operating.

OBJECTIVES: The objective is to obtain data and analyze the electrical impacts to the utilities' distribution system and quality of power delivered to the utilities' customers with the WTS voltage regulator operated in both the constant power factor mode and the constant terminal voltage mode.

APPROACH: Oscillograms of 3-phase currents and voltages have been obtained at Goodnoe Hills Substation during the initial synchronization of each MOD-2 WTS. Both 69 kV and 12.5 kV bus voltages are continuously monitored at all times. The voltage chart records will record any changes to the bus voltages when the MOD-2 are synchronized and operating.

Data will be obtained initially with one, two, and three WTS's under constant power factor control. Data will also be obtained with the generator voltage regulators connected for constant generator terminal voltage control.

TEST MATRIX: Baseline data will be obtained of voltages without the WTS synchronized and operating on the power system. The data obtained with the WTS in operation will be analyzed to evaluate any impacts and the quality of wind generated power in both the voltage regulator modes.

8.4.2 Validation of WTS Simulation Model

The response of single and multi-machine WTS installations to operating disturbances will be used to validate the simulation models and verify dynamic electrical system performance.

OBJECTIVES: The objectives of these field tests are to:

1. Validate the various models used to simulate the MOD-2 WTS. The simulation models used in the stability studies prepared for DOE and NASA-Lewis Research Center include the following:
   A. MOD-2 Wind Turbine Farm Stability Study by E.N.Hinrichen and P. J. Nolan of Power Technologies, Inc., June 1980 DOE/NASA 0134-1 NASA CR-1651562.
2. Verify the operation and response of the WTS's to disturbances impacting the electrical power system.

APPROACH: The configuration for these tests will be with the WTS's complete and electrically integrated into the power system. The Digital Data Acquisition Systems will be calibrated and in service. The analog data channels - 11 from each WTS - (discriminators and other equipment provided by BEC) will be in service. Tests shall be made with windspeeds sufficient to generate at least an average power output of 1.5 MW from each WTS.

Part I WTS Unit Trip

Tripping one unit with three operating at normal load will provide an excellent means to excite generator swing modes on the remaining two units for simulation verification. Recorded data on the tripped unit will also provide an opportunity for verifying performance and the simulation under off-nominal frequency operation. This test can be accomplished by simulating a fault causing either the Bus Tie Contractor or the Generator Breaker to trip open.

Part II Continuous Monitoring Mode

The data for Part II will be obtained under the continuous monitoring mode. Disturbances on the power system may be of sufficient magnitude to cause generator power swings to trigger the BPA Digital DAS in the high-speed data mode.

Automatic triggering is expected to occur for start/stop operations, power swings, strong wind gusts, and high wind speeds.

TEST MATRIX: Data will be used to validate the MOD-2 Model used by PTI, Boeing, and others for stability studies of single and multi-unit installations. BPA will analyze the dynamic impact of the WTS units on the electrical power system for start-up, steady state, line interrupts, and various re-synchronization modes.

8.4.3 Wind Turbine Generator Power Variation Analysis

A time series analysis will be performed on recorded fluctuations in wind generator outputs, to estimate the coherencey of wind inputs to the generator units. It is anticipated that fluctuations in power system conditions will also provide an input to the wind machines, and will require analysis to enable separation of the two effects.

<u>OBJECTIVES</u>: The objectives of these tests are to:

1. Determine the reliability and statistical characteristics of electrical power derived from wind resources.
2. Derive data from which the influence of wind generator placement upon overall power production can be determined.
3. Assess the likelihood of adverse interactions between the power system and the wind generation facility.
4. Provide selected database for use in evaluating future wind farm deployments.

<u>APPROACH</u>: High-speed data records will be taken under rated load conditions with one, two, and three MOD-2 WTS's on line under no disturbance conditions for frequency spectrum analysis. The long-term (background mode) data will be recorded to monitor the selected parameters of the WTS's and sensors from the meterological towers.

<u>TEST MATRIX</u>: Results of the time series analysis will include:

1. Spectral estimates for wind power fluctuations.
2. Inter-machine coherency spectra.
3. Spectral estimates for noise disturbances injected into the wind generation facility by the power system.

8.5 Machine Dynamics and Structural Analysis

During the first year of this overall project plan this test area shall be fully defined and implemented by a lead test project organization.

OBJECTIVE: The main objective is to obtain appropriate deflections, stresses, and responses of the WTS that will permit correlation of analytical predictions made from using the NASTRAN, MOSTAB, NACA/AMES STABILITY, EASY, AND LSD computer codes. Another objective is to identify possible structural "hot spots" in the WTS.

Extensive data will be taken on unit 2 in both the parked and operating modes in order to establish the structural characteristics of various components and to determine system responses for comparison with analytical predictions. Any measurements identified in early testing of unit 2 that merit additional monitoring on units 1 and 3 will be included in abbreviated measurements on those units.

APPROACH: Data will be taken through the complete operating envelope as well as continuously while parked to measure exposure to high winds and seismic excitation.

All three wind turbines will be completely instrumented with strain gauges, accelerometers, position and rate potentiometers, pressure gauges, temperature measuring devices and wind speed and direction indicators.

TEST MATRIX: To be defined.

8.6 Meteorological Data

A detailed understanding of the temporal and spacial characteristics of wind patterns and other meteorological parameters is a critical requirement of the Mod-2 cluster test program. A lack of understanding of many meteorological parameters could generate gaps in understanding many of the performance characteristics of the turbines.

Since this program will produce an extensive meteorological data base for use in other research endeavors, meteorological parameters from one and possibly two meteorological towers, and turbine output parameters from the three machines, will be recorded continuously on a centralized digital data logging system. In addition, it is anticipated that several short-term, intensive field measurement programs will produce a considerable amount of meteorological data from the site. All these data will be incorporated into a data base where information is readily retrievable.

OBJECTIVE: (1) to define general climatological conditions at the site, including mean and turbulent wind patterns measured temporally and spatially, vertical variation of wind characteristics, and vertical and horizontal temperature patterns, and (2) to provide information to be used in evaluating turbine performance evaluations, including the effect that upwind turbines have on downwind turbines due to wakes.

APPROACH: To achieve the first objective several years of high-quality recovery rate data are required. The second objective is achieved by concurrently measuring both meteorological and turbine parameters and recording the information on the same medium. To achieve these objectives, a 350-ft meteorological tower has been installed at the east end of the site by PNL. In addition, the BPA has installed a 200-ft tower at the

west end of the site. These two towers will provide the basis of meteorological measurements to help meet the two objectives. In addition, concurrent data from these systems during turbine operations should provide some insight into atmospheric turbulence levels both upwind and downwind of an operating Mod-2.

TEST MATRIX: Data acquisition to support study of the wind characteristics of the site and providing concurrent meteorological and turbine parameter data will be done routinely throughout the testing program. The only exception to this is when the system is down for calibration activities or unexpected sensor or system failures. Acquisition of high speed meteorological and turbine parameter data will be generally done to support wake study testing, unique turbulence experiments, or other research projects. High-speed data acquisition experiments will be administered by PNL.

During the test program meteorological data will be collected to establish the site climatology. In this mode, data are collected nominally at 2-minute intervals. A full range of meteorological conditions should be experienced through the test program. Turbine parameter data will be collected simultaneously. Thus, the relationship of site meteorology and machine operating conditions can be established.

8.7 Wake Effects Tests

8.7.1 Wake Structure Measurements

This task will be accomplished through a series of field programs during which PNL or its subcontractors will make measurements of wind speed and turbulence intensity at various positions around active or inactive wind turbines. The principal sensors will be balloon-borne or other tethered airborne telemetering instrument systems. Some measurements will be made with no impact on turbine operations and others should be made with the turbine running for 20 minutes, then shut down for 20 min. Tracer smoke releases will be made during some of the studies to photographically document the structure of the wake. Details are described below.

OBJECTIVE: To measure and visually document the structure of the MOD-2 wake as a function of position in the time-average wake under a broad class of ambient atmospheric conditions.

APPROACH: Measurements of wind velocity, turbulence intensity, temperature, and height above ground will be made at locations 1 and 2 rotor diameters upwind and between 1 and 10 diameters downwind of each MOD-2. Measurements lateral to the wake centerline will also be made. Primary emphasis, however, will be downwind of turbine #3 during westerly winds. Turbine power output and yaw error are the only turbine parameters required. Wind measurements will be made for as broad a range of wind speeds and Cp as possible, and under as wide a range of atmospheric stability, ambient turbulence intensity, and wind shear as possible. This

would require some night measurements and nighttime coordination with turbine operations. Measurements will only be made in non-precipitating conditions; however, some instrument shelter is required, as described under facility requirements. Atmospheric conditions will also be monitored from the two large towers at the Goodnoe Hills site. This would require stepping up the sampling and recording rate sufficient to measure a turbulence intensity from the tower sensors. It is, however, currently understood that the BPA tower is not appropriately instrumented for turbulence intensity measurements. The fundamental stability parameter for these measurements will be the gradient Richardson number measured from the towers and profile measurements from the tethered balloons. Some spot monitoring during the field program will be made with kite anemometers to assist in relocating the balloon packages.

TEST MATRIX: Preliminary smoke visualization tests would be made in early 1982 prior to the instrument measurement program to assess the feasibility of this technique. During this test, one or two smoke releases would be made from the nacelle and from the elevated platform upwind of one of the turbines. If this technique is viable, additional releases would be made during the various atmospheric and operation conditions being sampled in the phases 1 and 2 measurement program. Field measurements will be spread over four phases. Each phase is one week long. During phases 1 and 2, measurements along and normal to the wind turbine wake centerline will be made with no requirements upon turbine operations. Approximately eight runs will be executed per day where a run consists of a wind velocity and temperature profile

measurement, a fixed-level measurement of 20 minutes duration, finishing with a profile measurement. One, two, or three instrument packages may be aloft at one time. Following a run, the positions of the ground stations will be relocated before the next run. Quick kite anemometer probes may be of some assistance in relocating the ground station. The rationale for two phases in the same operational mode is for an initial shakedown of the method, and to separate the sample into two independent weather regimes.

Phase 3 and 4 modes of operation are similar except coordination with wind turbine operations are necessary. Of the eight runs made per day, the wind turbine would be requested to shut down in wind speeds near the Cp maximum up to four times per day.

8.7.2 Wake Effects on Performance

OBJECTIVE: To determine the extent of wake effects on the performance of a downwind wind turbine at separations of 5, 7, and 10 rotor diameter and a variety of ambient atmospheric conditions.

APPROACH: In this activity, the MOD-2 wind turbine will serve as the wake sensor. At various times during cluster operation as the wind is aligned with two turbines along either the 5, 7, or 10 diameter spacings, the upwind turbine will be shut down and re-started to assess the wake effects, if any, upon the downwind turbine. Analysis of the effects of wake turbulence and dynamic loads will be carried out by BEC. The role of PNL will be to coordinate with BEC and BPA to assure that a full spectrum of atmospheric conditions are sampled during these experiments. PNL

will also analyze the impacts of wakes upon power output as a function of atmospheric conditions. The statistical significance of any observed wake effects on power output and loading will be assessed so that recommendations on spacing can be made.

TEST MATRIX: It is estimated that 25 run-shutdown-run cycles are required across each of the three turbine separations. This is probably easy to achieve for the situation where WTS #3 is upwind of WTS #1 but more difficult for the other orientations. It remains to be worked out how the less frequent cases could be achieved. One possibility is through monitoring the meteorological data (from either PNL, BEC, or LeRC) through the dial-up system and when conditions are appropriate, request turbine shut-down. If personnel are required to be onsite during these procedures, data collection for the less frequent wind direction cases may be made considerably more difficult.

8.8 Cluster/Array Analysis

Based on the wake interference and the turbine/grid security information obtained during the first year of research experiments, analyses will be made to:

(a) evaluate the orientation and spacing between turbines to optimize the cost effectiveness of energy production

(b) establish the cost effectiveness of wind arrays optimized for grid security (plant availability factor).

(c) evaluate the turbine wakes in terms of orientation and spacing in order to minimize or mitigate the production of annoying acoustic emissions.

Specific objectives, the approach, and definitive plans will be formulated in early CY 83.

8.9 Array Maintenance Evaluation

The effect on costs, schedule, and availability for various array maintenance options shall be evaluated. Wind Turbine System arrays can be characterized for maintenance as consisting of single machines or as clusters. Priorities must be established regarding the immediate repair of a single machine or delayed maintenance of multiple units within the array.

APPROACH: This part of the Operational Field Testing for array maintenance evaluation will be a BPA/BEC joint effort. Appropriate logs, and reporting procedures, will be devised to provide the required information and data for the database.

The data and information will be used as input for preparing various summaries. The reports will give the results of the

analysis of maintenance options relating the maintenance to energy production, cost of energy, and cost of maintenance.

The powerplant performance indices used by the industry will be used and modified as appropriate for presenting performance evaluation of wind turbine systems individually and as an array.

Powerplant Performance Indices

$$\text{Capacity Factor} = \frac{\text{Total Gross Generation in MW-hr}}{(\text{Period Hours}) \times (\text{Maximum Dependable Capacity})} \quad \text{Units MW}$$

$$\text{Availability Factor} = \frac{\text{Available Hours}}{\text{Period Hours}}$$

$$\text{Equivalent Availability} = \frac{(\text{Available Hours}) - (\text{Equivalent Forced and scheduled Outage Hours})}{\text{Period Hours}}$$

$$\text{Forced Outage Rate} = \frac{\text{Forced Outage Hours}}{(\text{Service Hours}) + \text{Forced Outage Hours}}$$

8.10 Advanced Concepts Verification

Verification of advanced concepts (generation as well as transmission) may be performed. However, a determination must be made previously to assure minimal impact on program/project goals and objectives.

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16. Abstract
Upon completion of the design and development of three Mod-2 wind turbines at Goldendale, Washington, a series of research experiments are planned to gather data on and evaluate the performance, environmental effects, and operation of a cluster as well as a single, large multimegawatt wind turbine. This test project plan addresses the test program and is divided into two volumes. This volume (initial plan), distributed to the private sector, includes information on the program objectives, a Mod-2 system description, a planned schedule, organizational roles, and responsibilities. Volume II, a continuously updated test operations document, provides detailed test plans and specific tests prepared by the Lead Test Organizations and approved by a Test Project Review Board and has a limited distribution as a working document. Supportive efforts were provided by Boeing Engineering and Construction, Bonneville Power Administration, Battelle Pacific Northwest Laboratories, and the Solar Energy Research Institute.

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